

DOT/FAA/TC-17/63

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Round Robin Evaluation of CACRC Bonded Repairs

November 2017

Final Report

This document is available to the U.S. public through the National Technical Information Services (NTIS), Springfield, Virginia 22161.

This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.



U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof. The U.S. Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the objective of this report. The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the funding agency. This document does not constitute FAA policy. Consult the FAA sponsoring organization listed on the Technical Documentation page as to its use.

This report is available at the Federal Aviation Administration William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov in Adobe Acrobat portable document format (PDF).

1. Report No. DOT/FAA/TC-17/63	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle ROUND ROBIN EVALUATION OF CACRC BONDED REPAIRS		5. Report Date November 2017	
		6. Performing Organization Code AIR-100	
7. Author(s) John Tomblin, Lamia Salah, John Welch, Mike Borgman, Brian Kitt, Chathuranga Kuruppuarachchige, Ruchira Walimunige		8. Performing Organization Report No.	
9. Performing Organization Name and Address National Institute for Aviation Research Wichita State University 1845 Fairmount St, Wichita, KS 67260		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation FAA Northwest Mountain Regional Office 1601 Lind Ave SW Renton, WA 98057		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code AIR-100	
15. Supplementary Notes The FAA William J. Hughes Technical Center Aviation Research Division CORs were Lynn Pham and Curtis Davies.			
16. Abstract The objective of this research was to evaluate the existing Commercial Aircraft Composite Repair Committee (CACRC) standards and approved materials used for repair of composite airframe structures, and to assess the repair process variability between depots and technicians with different experience and training levels. The overall research approach involved manufacturing composite repair sandwich elements representative of composite aircraft production parts using original equipment manufacturer (OEM) materials and processes, and repairing these elements using OEM factory and CACRC field methods and materials. The repair static and residual strength after cyclic loading were evaluated under severe temperature and moisture environments, and key elements in the process and implementation of the repairs were reported. The research revealed that CACRC standards cannot be used as a sole document to repair a composite part and that a part-specific document is required. These standards are intended to provide best practices for repairs and not replace repair documents. Process checklists used to document the repair-process steps showed several process deviations and mistakes that yielded deficient repairs. The research showed variability in the repair residual-strength results between depots and mechanics with the wet lay-up repairs yielding a higher scatter than prepreg repairs. Research results also underscored that repairmen experience alone is not a predictor of repair performance, and demonstrated the importance of workforce education and training for the proper execution of bonded repairs to composite substrates. Part- and process-specific training of the composite repair workforce, taking into account the process learning curve, is strongly recommended. Process inspection and quality assurance oversight are also strongly advocated. The research results also show the importance of repair process development, substantiation, and execution, and that a robust repair design and execution will yield strong, durable bonded repairs.			
17. Key Words Commercial Aircraft Composite Repair Committee (CACRC), Composite bonded repairs		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the FAA William J. Hughes Technical Center at actlibrary.tc.faa.gov .	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 90	22. Price

ACKNOWLEDGMENTS

The authors would like to thank all the industry sponsors from Spirit Aerosystems. The Commercial Aircraft Composite Repair Committee (CACRC), Aviation Technology Associates, NORDAM, and Hexcel: John Welch, Mike Borgman, Brian Kitt, Ray Kaiser, Nathan Schulz, Eric Chesmar, Jerry Dean, Marc G. Felice, Suranga Nagendra, Jan Popp, Francois Museux, Rusty Keller, and Justin Hamilton. The authors are also very grateful for the invaluable input of the CACRC members: Larry Sullivan, Ana Rodriguez, and Francois Museux.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	xi
1. INTRODUCTION/ RESEARCH OBJECTIVES	1
2. BACKGROUND/ LESSONS LEARNED FROM PREVIOUS WORK	2
3. RESEARCH INVESTIGATIVE PLAN	4
3.1 Base Panel Manufacturing Procedure	5
3.2 Specimen Preparation	11
3.3 CACRC Round Robin Test Matrix	13
3.4 Specimen Design Validation	16
3.5 Repair Procedures	18
3.5.1 CACRC R1 Prepreg Repair Procedure	18
3.5.2 CACRC R2 Wet Lay-Up Repair Procedure	23
3.5.3 OEM R1 Prepreg Repair Procedure	27
3.5.4 OEM R2 Wet Lay-Up Repair Procedure	27
3.6 CACRC Depot Mechanic Survey Results Summary	30
3.7 CACRC Depot and OEM Repairs Process Summary	34
4. MECHANICAL TESTING	42
4.1 Moisture Conditioning	42
4.2 Specimen Instrumentation	43
4.3 Long Beam Flexure Static and Fatigue Test Procedure	44
4.4 Test Results	49
4.4.1 Prepreg Repair Test Results (CACRC-R1 and OEM-R1 materials)	49
4.4.2 Prepreg Repair Failure Modes:	52
4.4.3 Prepreg Repair Variability by Operator	55
4.4.4 Non-Destructive Inspection after Repair	55
4.4.5 Prepreg Repair Post-Test Analysis	60
4.4.6 Wet Lay-Up Repair Test Results (CACRC-R2 and OEM-R2 materials)	63
4.4.7 Wet Lay-Up Repair Failure Modes	65
4.4.8 Wet Lay-Up Repair Variability by Operator	67
4.4.9 Wet Lay-Up Non-Destructive Inspection after Repair	68
4.4.10 Wet Lay-Up Repair Post-Test Analysis	70
5. CONCLUSIONS AND RECOMMENDATIONS	73
6. REFERENCES	75

LIST OF FIGURES

Figure	Page
1 In-service damage [2]	1
2 Design load and damage considerations for durability and design [3]	3
3 Representative test panel geometry	5
4 Representative cure cycle for facesheet 1	6
5 Core sheet 36 x 98 inches, as delivered (ribbon direction along 36-inch width)	8
6 Core preparation for cutting	8
7 Potting compound application onto core	9
8 Facesheet (a) 1 lay-up and (b) adhesive application	9
9 Uncured assembly 1 (facesheet 1, film adhesive and filled core)	9
10 Assembly 1 bagging and preparation for cure	10
11 Cured assembly 1 prepared for final assembly	10
12 Final assembly (cured assembly 1 and uncured facesheet 2)	10
13 Final assembly/CACRC -001-0101 panel	11
14 Large-beam drawing	12
15 Large-beam machining	12
16 Machined elements prior to repair	12
17 Large-beam configuration	13
18 CACRC prepreg and wet lay-up repair materials	16
19 CACRC round robin baseline specimen-failure modes	18
20 Scarf-sanded panel ready for repair	20
21 Repair adhesive and ply application	21
22 Bagging procedure (no-bleed cure) [29]	22
23 Scarf sanded panel ready for repair	24
24 Epocast 52A/B resin mixing	25
25 Dry-fiber impregnation with Epocast 52A/B resin	26
26 CACRC wet lay-up repair conducted at depot 1	34
27 CACRC prepreg repair conducted at depot 2	35
28 CACRC wet lay-up repairs conducted at depot 3	36
29 CACRC wet lay-up repairs conducted at depot 4	37
30 CACRC prepreg repairs conducted at depot 5	38

31	OEM prepreg repairs (conducted at the OEM factory)	39
32	OEM wet lay-up repairs conducted at NIAR; repair checklist review and findings; composite repair key processing parameters	40
33	Representative moisture conditioning chart for a CACRC repair element	43
34	CACRC repair-element strain-gauge layout	44
35	Isometric view of four-point bending test fixture	45
36	Long beam flexural test setup at room temperature	45
37	Long beam flexure elevated temperature test setup	47
38	Thermocouple placement on gauge section of repaired elements (top and bottom facesheets)	48
39	Temperature readings on gauge section of repaired elements	48
40	Round robin compression test results for all prepreg repairs tested at 180°F wet	51
41	Representative failure modes of baseline/undamaged elements tested at 180°F	52
42	Representative failure modes of open-hole scarfed elements (unrepaired) tested at 180°F (this configuration simulates a patch-off/completely failed repair condition)	53
43	Representative failure modes of CACRC prepreg repairs using M20PW/EA9695 (facesheet compression failure through the repair)	53
44	Representative failure modes of CACRC prepreg repairs using M20PW/ EA9695 (facesheet compression failure outside the repair, through the parent)	54
45	Representative failure modes of OEM-R1 prepreg repairs using T300/934 PW and FM377 adhesive (facesheet compression failure outside the repair, through the parent)	54
46	Round robin compression test results for CACRC prepreg repairs (M20 PW/ EA9695 adhesive tested at 180°F Wet) performed by different mechanics	55
47	CACRC-003-0201-003-P-RC-ETW (element 9), TTU scan, pre- and post-test picture (understrength repair)	56
48	CACRC-021-1101-001-P-RC-ETW (element 10), TTU scan, pre- and post-test picture (understrength repair)	56
49	CACRC-031-1601-003-P-RC-ETW (element 11), TTU scan, pre- and post-test picture (understrength repair)	57
50	CACRC-004-0202-001-P-RC-ETW (element 16), TTU scan, pre- and post-test picture (understrength repair)	57
51	CACRC-004-0202-002-P-RC-ETW (Panel 17), TTU scan, pre- and post-test picture (understrength repair)	58
52	CACRC-022-1102-001-P-RC-ETW (Panel 18), TTU scan, pre- and post-test picture (understrength repair)	58
53	CACRC-025-1301-002-P-RC-ETW (element 5), TTU scan and post-test picture	59

54	CACRC-015-0801-001-P-RC-ETWF (element 7), TTU scan, and post-test picture	59
55	CACRC-039-2001-001-P-RC-ETW (element 33), TTU scan and post-test picture	60
56	CACRC post-test analysis map	60
57	CACRC-004-0202-02-PM-C	62
58	CACRC-004-0202-02-PM-B	62
59	CACRC-037-1901-03-PM-C	62
60	CACRC-037-1901-03-PM-B	62
61	Round robin compression test results for all wet lay-up repairs tested at 180°F wet	64
62	Representative failure modes of CACRC wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (facesheet compression failure through the repair)	65
63	Representative failure modes of CACRC-R2 wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (facesheet compression failure outside the repair, through the parent)	65
64	Representative failure modes of CACRC-R2 wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (adhesion failures)	66
65	Representative failure modes of OEM-R2 wet lay-up repairs using T300 3K fabric, EA9396 C2 laminating resin, and EA9696 adhesive (facesheet compression failure outside the repair, through the parent)	66
66	Representative failure modes of OEM-R2 wet lay-up repairs using T300 3K fabric, EA9396 C2 laminating resin, and EA9696 adhesive (facesheet compression failure through the repair)	66
67	Round robin compression test results for CACRC wet lay-up repairs (tested at 180°F wet) performed by different mechanics	67
68	CACRC-004-0202-003-W-RC-ETW (element 21), TTU scan, pre- and post-test picture (adhesion failure)	68
69	CACRC-022-1102-002-W-RC-ETW (element 23), TTU scan, pre- and post-test picture (adhesion failure)	68
70	CACRC-032-1602-002-W-RC-ETW (element 32), TTU scan, pre- and post-test picture (understrength repair, facesheet compression failure through repair)	69
71	CACRC-005-0301-001-W-RC-ETW (element 10), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)	69
72	CACRC-006-0302-001-W-RC-ETW (element 24), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)	70
73	CACRC-006-0302-003-W-RC-ETW (element 27), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)	70
74	CACRC-023-1201-002 section B	72
75	CACRC-023-1201-002 section C	72

76	CACRC-006-0302-003 section B	72
77	CACRC-006-0302-003 section C	72

LIST OF TABLES

Table		Page
1	Parent material specifications	6
2	Repair material specifications	7
3	Stacking sequence, CACRC panels CACRC 0101–2002	7
4	CACRC round robin phase panel ID	7
5	Coupon conformity list	11
6	CACRC round robin test matrix	15
7	Pristine (undamaged) specimen strength (RTA)	17
8	Cure cycle for CACRC prepreg repair material	23
9	Cure cycle for CACRC wet lay-up repair material Cure	27
10	cycle for CACRC OEM wet lay-up repair material	30
11	CACRC depot mechanic survey responses	31

LIST OF ACRONYMS

AC	Advisory Circular
CACRC	Commercial Aircraft Composite Repair Committee
CFR	Code of Federal Regulations
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimeter
ETW	Elevated temperature wet
NCAT	National Center for Aviation Training
NDI	Non-destructive inspection
NIAR	National Institute for Aviation Research
OEM	Original equipment manufacturer
OJT	On-the-job training
PNL	Panel
RH	Relative humidity
QA	Quality assurance
RTA	Room temperature ambient
SRM	Structural repair manual
TTU	Through-transmission ultrasonics

EXECUTIVE SUMMARY

The long-term durability of adhesively bonded structures and repairs is a key element in the acceptance and implementation of bonded technology by original equipment manufacturers and operators in the repair of composite primary structural elements. Weak interfacial bonds between composite substrates resulting from a deficient process are not detectable by current inspection methods and might degrade as the component is in service, subjected to loading and the environment. With the lack of inspection methods to warrant the integrity of a composite substrate's interface prior to bonding or to detect deficient bonds, there is a concern that undetected weak bonds or understrength repairs may further deteriorate in service, potentially leading to the failure of the repaired part. A robust infrastructure for bonded composite structure maintenance and repair is necessary to ensure the durability of airframe composite components.

The objective of this research was to evaluate existing Commercial Aircraft Composite Repair Committee (CACRC) standards and qualified materials for repair of composite structures, to assess the repair process variability between depots using the same repair document procedures based on CACRC repair techniques and provided repair materials, and to investigate the variability associated with technician training on the performance of the repair. The ultimate goal was to compare strength of the different repairs to sets of control "pristine" panels and open-hole scarfed panels simulating a patch-off condition, and to evaluate the environmental effects on the static and residual strength after fatigue of these repairs. The objectives of this research work were met by round robin testing of the repairs at different depots.

CACRC standards cannot be used as a sole document to repair a composite part. Research results showed that these standards represent best practices/techniques for repair and a part-specific document is required. The CACRC standards can however be used along with an SRM or other part specific document. It is ultimately the repair designer's responsibility to select which standards to use for the specific repair.

The study also showed variability in residual strength results between depots and mechanics with the wet lay-up repairs yielding a higher scatter than the prepreg repairs. Results underscored that repair technician experience alone is not a predictor of repair performance. The prepreg repairs yielded six understrength repairs but no adhesion failures. (Understrength repairs are repairs that fail to achieve the predicted strength value.). The wet lay-up repairs yielded three adhesion failures. The six CACRC prepreg understrength repairs were performed by either an experienced operator or a technician with minimal experience. Similarly, the three CACRC wet lay-up repairs yielding adhesion failures were all performed by an experienced operator.

The feedback received from depot personnel and the results of the round robin testing demonstrate the importance of workforce education and training for the proper execution of bonded composite repairs to composite substrates. Part- and repair-process-specific trainings of the composite repair workforce, taking into account the process learning curve as well as repair process inspection and quality inspection, are strongly recommended.

Detailed repair records must be kept to ensure repair process control and stability, and to detect and correct for process failures and deviations. Process checklists used in the depots to control the

quality of the repairs revealed numerous process deviations and mistakes during the repair execution. The following critical composite repair processing parameters were identified:

Environment/ Timeframe for Repair Execution

- Repair Station Environment
- Timeframe for repair performance and execution

Repair materials

- Repair Material out time and storage life
- Batches of materials used

Panel Preparation/Inspection Prior to Repair

- Surface preparation
- Quality of the repair scarf (morphology)
- Fitness of the interface for bonding (pre-bond moisture, contamination)

Repair Application

- Time lag between surface preparation and repair application
- Number of filler plies (when applicable)
- Ply alignment/ sequence
- Resin Mixing Ratios (Wet Lay-up Repairs)
- Resin Work Life (Pot Life, Wet Lay-up Repairs)

Repair Cure

- Repair Bagging Scheme and Materials
- Heat Blanket and Thermocouple Installation (Hot Bonder Calibration)
- Time lag between drying and final cure
- Repair Cure Cycle Ramp Up Rate
- Repair Cure Dwell Time

Vacuum Level Achieved during Repair cure (sea level, high altitude)

Research results also demonstrate the importance of repair-process development, substantiation, and execution. Process substantiation should include understanding of critical process steps and parameters affecting the repair performance, and the consequences of bad process implementation. Because of the chemical characteristics of various systems used for bonding and repair, it is very important to understand the capabilities and limitations of the specific systems, especially when they are close to the end of their storage or work life limits. It is also important to understand the importance of proper bagging and the effects of cure-cycle parameters, such as temperature ramp-up rates, dwell time, and vacuum levels on the performance of the repair. The use of adequate

processes specific to the materials used is key to the structural integrity of the repaired part. Caution should be exercised when applying results from one material system to the next.

Knowledge transfer in the form of training, validated repair instructions and repair records, and documentation are integral to ensuring repair process repeatability, stability, and structural integrity of the repaired component. Detailed records and documentation are necessary to ensure strict adherence to the process. As shown by the results, a deficient process may result in understrength or completely failed repairs. Finally, a robust repair design and execution will yield strong, durable bonded repairs.

1. INTRODUCTION/RESEARCH OBJECTIVES

Major technological advances using fiber-reinforced composite materials in airframe components have improved performance and promoted energy efficiency over the last 50 years, leading to the introduction of these materials in load-bearing wing and fuselage structures. Durability, repairability, and maintainability are key elements in the continued airworthiness of composite structures. Challenges associated with composite repair and supportability of composite structures are of particular interest and must be addressed during the design phase of the component. Rigorous material, structural and repair process substantiation, validation, and execution are crucial to ensure the structural integrity of bonded composite structures and repairs.

The use of fiber-reinforced composites in aircraft structural components has significantly increased over the last few decades because of their improved specific strength and stiffness, the ability to be tailored to design requirements in various loading directions, manufacturability, the possibility of building a composite part in a single integral shell, and superior corrosion resistance and fatigue endurance when compared to metallic components. These features offer a great potential for weight savings, reduction in maintenance, and operating costs resulting in more cost-efficient and profitable airframes [1]. To capitalize on the performance benefits these materials offer, numerous technological challenges must be overcome in various disciplines. One of the most critical is repair and maintenance. As most maintenance and repair depots and facilities prepare for this new generation of composite airframe components, it is essential that the infrastructure for supportability is in place to maintain these structures and ensure their airworthiness and structural integrity. Figure 1 shows an example of in-service damage to an aircraft fuselage.



Figure 1. In-service damage [2]

One of the main challenges in bonded-repair technology is the limited capability of current non-destructive inspection (NDI) methods in detecting weak bonds. Weak interfacial bonds between composite substrates resulting from a deficient process or a compromised interface are not detectable by current NDI methods, and the bonds might degrade as the component is subjected to loading and the environment while in service. Consequently, an understrength repair may not be detected until it actually disbonds, leading to a possible failure of the repaired part. Therefore, it is

essential to rely on rigorous bond quality management, repair definition, and process execution to achieve repeatable and structurally reliable bonded repairs.

The objective of this research effort is to evaluate existing Commercial Aircraft Composite Repair Committee (CACRC) standards for repair of composite structures. This study is used to assess the repair process variability among multiple operator depots, using structural repair manual (SRM)-like procedures and referencing CACRC repair techniques provided to all the depots. The variability associated with technician training, identified as a key element in the repair performance in a previous study, is also investigated. The ultimate strength and durability of original equipment manufacturer (OEM) 350°F-cure repairs is compared to that of the CACRC repairs and to a set of pristine control and scarfed open-hole panels to establish the residual strength of these repaired components. This research is also used to evaluate the environmental effects on the ultimate strength and residual strength after fatigue of these bonded repairs.

The overall goal of the study is to identify areas of improvement in the existing repair standards, repair procedures, and standardized techniques that can be used across OEMs, airlines, and repair stations. Results can then be used to identify critical steps in the execution of bonded repairs and to provide recommendations pertaining to existing CACRC standards, the durability of the CACRC materials approved for repair, repair technician training, and repair process control. Results from the study can also be used to promote awareness of the challenges associated with composite repair and to provide recommendations in composite repair awareness courses, training curriculum, safety initiatives, and policies.

2. BACKGROUND/LESSONS LEARNED FROM PREVIOUS WORK

A repair has the objective of restoring a damaged structure to its undamaged state in terms of strength, durability, stiffness, functional performance, safety, cosmetic appearance, or service life. The design assessment of a repair for a given loading condition involves the selection of a repair concept and the choice of the appropriate repair materials and processes, then specifying the detailed configuration and size of the repair [3]. Designing for repairability is an essential element in the effective use of composite materials in aircraft structures. It is important that the repair philosophy be set during the conceptual design stage and that the repair designs be developed along with the component design [4]. Composite structures must be designed to be durable, repairable, and maintainable. Durability implies that the component can maintain its structural integrity in terms of strength, stiffness, and environmental resistance throughout its lifetime. Repairability implies that repair philosophies for these structures have to be developed during the design phase. Maintainability is a key element in composite design: simple assemblies, easily accessible for internal inspection, are preferred to minimize damage during maintenance [4].

Composite primary airframe structure substantiation requirements are set forth in Title 14 Code of Federal Regulations (CFR) Part 23.573 (a) with special considerations for damage tolerance, fatigue, and bonded joints. For any bonded joint, 14 CFR 23.573 states in part “the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods...” These same standards apply to commercial transport and rotorcraft category aircraft (via special conditions and issue papers) [5]. Applicable airworthiness standards for transport category airplanes include 14 CFR 25.603 materials, 25.605 fabrication methods, 25.613 material strength properties and design values, and 25.571 damage tolerance and

fatigue evaluation of structure. Advisory Circular (AC) 20-107B – Proof of structure – Static states that “the effects of repeated loading and environmental exposure which may result in material property degradation should be addressed in the static strength evaluation” [5]. AC 20-107B – Proof of structure – Fatigue and Damage Tolerance states “...Such evaluation must show that catastrophic failure due to fatigue, environmental effects, manufacturing defects or accidental damage will be avoided throughout the operational life of the aircraft.” AC 20-107B – Proof of structure – Continued Airworthiness states that “...Of particular safety concerns are the issues associated with bond material capabilities, bond surface preparation, cure thermal management...” [5].

Adhesively bonded repairs have significant advantages over bolted repairs. Adhesively bonded repairs can restore a composite structure’s original strength, are more fatigue resistant because of the absence of stress concentrations that occur at fasteners, and are significantly lighter than bolted repairs because of the absence of fastener hardware. Adhesively bonded repairs have limitations because a bonded joint is a single joint, so there is no redundancy in the load path. Furthermore, there are no current NDI methods that can provide assurance of absolute bond integrity. Adhesively bonded repairs are process dependent and, therefore, repair technicians must have adequate training and competency to successfully complete the bonding process.

As more composite materials are used in aircraft structural components, it is important to develop repair philosophies that restore the structure to its original design capability. This implies development of maintenance procedures that clearly define the allowable damage limit for the structure and provide efficient and reliable NDI and repair methods (figure 2).

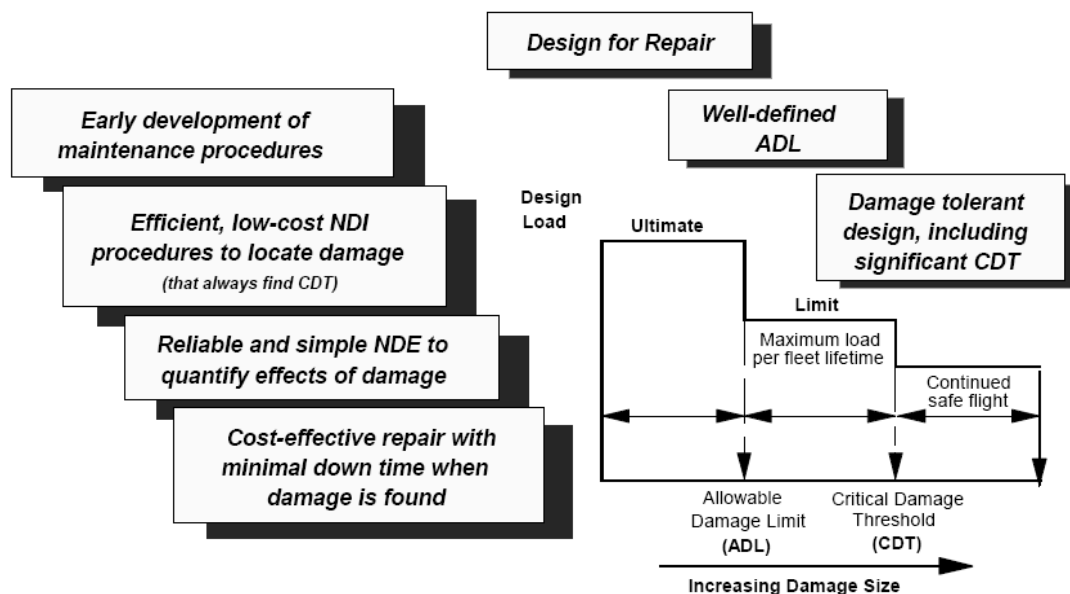


Figure 2. Design load and damage considerations for durability and design [3]

Many lessons can be learned from the experience acquired with existing metallic components. In-service experience with bonded composite repairs to metallic airframes over 20 years has demonstrated outstanding performance in terms of cost, effectiveness, and environmental

durability. Reliable processes have been used in the application of these repairs [6], but there have been numerous in-service failures in which deficient processes were used [7, 8]. A survey of defects reported by the Royal Australian Air Force showed that adhesive bond failures accounted for 53% of the deficiencies reported. Most reported failures can be attributed to adhesion failures due to bond interfacial degradation caused by either inadequate bonding processes or a moisture entry path adjacent to the failure site that caused hydration of the metallic substrates and subsequent bond deterioration [7, 8]. Rigorous surface preparation yielding a clean, chemically active interface resistant to environmental degradation is essential to ensuring the long-term durability of bonded repairs.

Numerous studies have demonstrated the importance of robust processes to ensure the structural integrity of bonded repairs to composite structures [9–12]. In the first study, an improper curing process resulted in understrength repairs with residual strengths equivalent to that of the open-hole unrepaired structure [9]. The second study considered the ability of forming a strong, durable bond with an already contaminated substrate [10]. The concern was the ability to bond a repair to a structure that has been in-service and has been exposed to the environment and to other contaminants. The results confirmed the detrimental effects of pre-bond contamination on the strength of bonded scarf repairs. Furthermore, moisture absorption may cause irreversible changes in the epoxy network, [11] inhibiting the formation of strong, durable bonds during repair. In-service experience with bonded repairs [12] showed multiple failures due to a silicone contaminated surface, pre-bond moisture, and ineffective cure all resulting in a weak repair that failed in service.

3. RESEARCH INVESTIGATIVE PLAN

Several objectives were defined for this research work. The first goal of the study was to evaluate existing CACRC standards for repair of composite structures using CACRC-approved materials. The second goal was to assess the repair process variability between depots using the same SRM-like procedures, repair techniques, and materials provided to all the depots. The third goal was to investigate the variability associated with technician training (minimal level of experience versus extensive experience) on the performance of the repairs. The final goal was to compare the strength of different repairs (CACRC-R1/R2 versus OEM R1/R2) to a set of control pristine panels and to a set of open-hole scarfed panels and to evaluate the environmental effects on the static and residual strength after fatigue of these repairs.

The following is a list of all OEM/airline depots and points of contact that were involved in this research effort:

- Delta Air Lines (Ray Kaiser, ray.kaiser@delta.com; Nathan Schulz, nathan.schulz@delta.com)
- United Airlines (Eric Chesmar, eric.chesmar@united.com; Jerry Dean, jerry.dean@united.com)
- Aviation Technology Associates (Marc G. Felice, mgfelice@avtechemail.com)
- NORDAM (Suranga Nagendra)
- Lufthansa Technik (Jan Popp)

- Spirit AeroSystems (John Welch, john.m.welch@spiritaero.com; Brian Kitt, brian.kitt@spiritaero.com; Mike Borgman, Michael.d.borgman@spiritero.com)
- Airbus (Francois Museux, francois.museux@airbus.com)
- The Boeing Company (Rusty Keller, russell.l.keller@boeing.com)
- Hexcel (Justin Hamilton, Justin.hamilton@hexcel.com)

All materials were supplied by the OEM, and all panel fabrication was conducted at the National Institute for Aviation Research/National Center for Aviation Training (NIAR/NCAT) facility using OEM-approved processes to ensure that the resulting repair elements were representative of production materials and processes.

3.1 BASE PANEL MANUFACTURING PROCEDURE

Forty large sandwich panels were manufactured for the purpose of this investigation, as shown in figure 3. The parent substrate is a 4-ply sandwich with 3/16-inch core cell size, 2 inches thick.

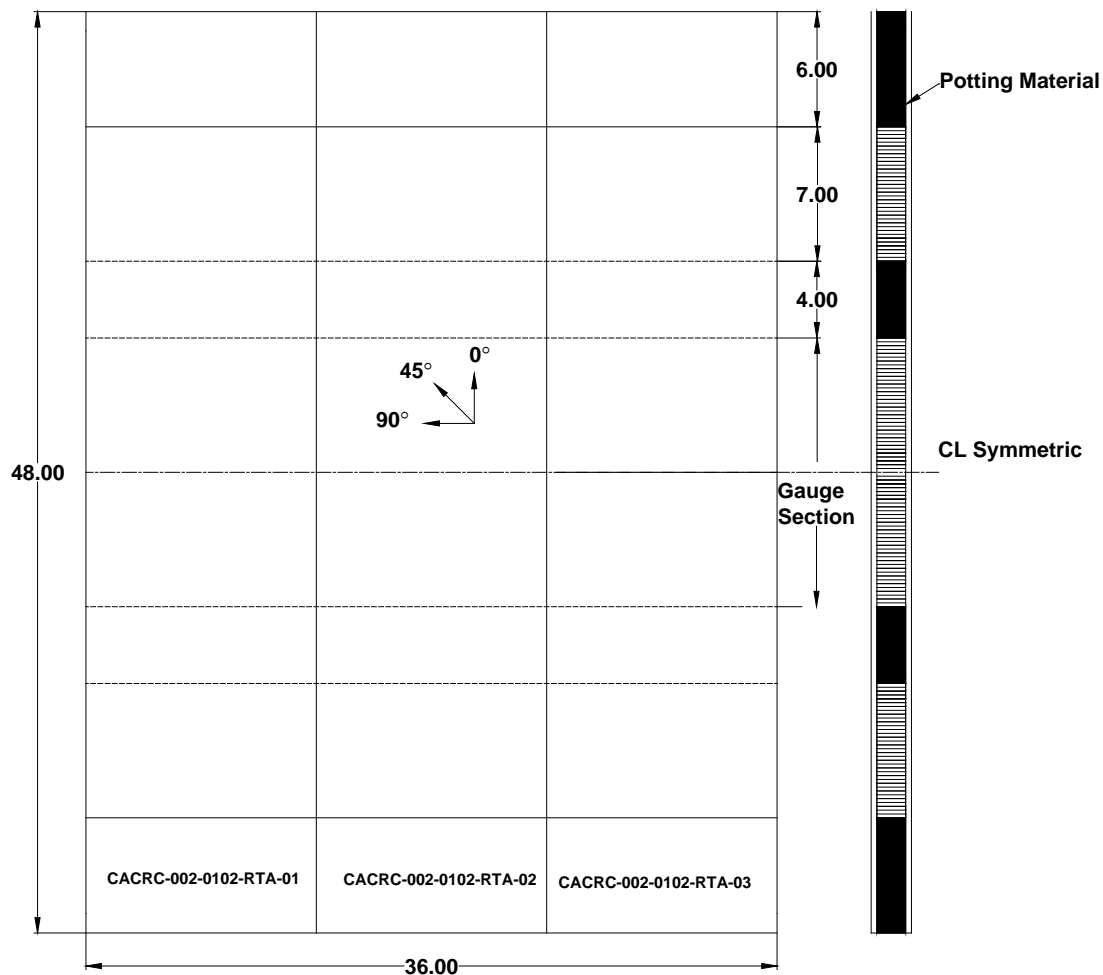


Figure 3. Representative test panel geometry

Before manufacturing the panels, a facility audit was conducted to demonstrate compliance with applicable OEM specifications. The OEM audit included, but was not limited to, inspection and review of received products and documentation, facility and equipment inspection, review and inspection of material handling and storage procedures, processing aides, and quality system. The OEM quality assurance (QA) inspectors reviewed and witnessed all planning, lay-up, processing, inspection, and testing documentation for the first panel built and granted approval to proceed with panel manufacture. Parent and repair materials and corresponding specifications are summarized in tables 1 and 2. Panel stacking sequence and identification are summarized in tables 3 and 4. All panels were fabricated using T300/934 PW prepreg, FM377U adhesive, Cytec Corfil 658 potting compound, and HRP-3/16-8 core with two layers of film adhesive. The 2-inch-thick sandwich panels were cured in two operations: a first operation in which facesheet 1 was cured with the core (including the potting compound) referred to as assembly 1, and a second operation in which facesheet 2 was bonded to assembly 1. The part was cured at 45 psi at 355 +/- 10°F for 2 hours with a 250°F hold for 25–45 minutes. A representative cure cycle is shown in figure 4.

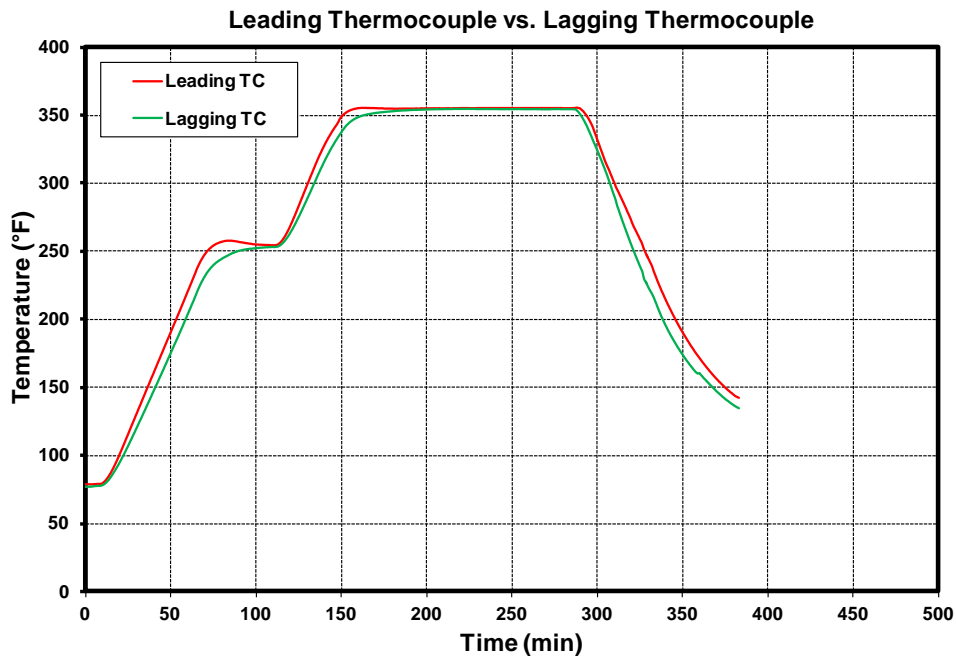


Figure 4. Representative cure cycle for facesheet 1

Table 1. Parent material specifications

Parent Materials	Vendor Name	Alternate Specification
Prepreg	Cycom 934 PW T300 3K	N/A
Film Adhesive	FM 377U Adhesive Film 0.055 psf	N/A
Core	HRP-3/16-8.0	N/A
Potting Compound	Cytec Corfil 658	N/A

Table 2. Repair material specifications

Repair Materials	Vendor Name	Alternate Specification
Prepreg	Cycom 934 PW T300 3K	N/A
Film Adhesive	FM 377K 0.08 psf Adhesive Film	N/A
Cytec Fabric	T300 3K PW	N/A
Paste Adhesive	EA 9396 C2	N/A
Film Adhesive	EA 9696	N/A
Laminating Resin	Huntsman Epocast® 52 A/B	SAE AMS 2980
Hexcel Fabric	G0904 D1070 TCT	SAE AMS 2980
Prepreg	Hexply M20/G904	SAE AMS 3970
Film Adhesive	EA9695NW 0.05psf	SAE AMS 3970

Table 3. Stacking sequence, CACRC panels CACRC 0101–2002

Stacking Sequence		
P1	0°/90°	PW
P2	±45°	PW
P3	±45°	PW
P4	0°/90°	PW

Table 4. CACRC round robin phase panel ID

Panel ID	Core ID	Geometry
CACRC-001 thru 40	0101 thru 2002	Figure 2

Panel List, Large Beams 2"-Thick Core			
CACRC-001-0101	CACRC-011-0601	CACRC-021-1101	CACRC-031-1601
CACRC-002-0102	CACRC-012-0602	CACRC-022-1102	CACRC-032-1602
CACRC-003-0201	CACRC-013-0701	CACRC-023-1201	CACRC-033-1701
CACRC-004-0202	CACRC-014-0702	CACRC-024-1202	CACRC-034-1702
CACRC-005-0301	CACRC-015-0801	CACRC-025-1301	CACRC-035-1801
CACRC-006-0302	CACRC-016-0802	CACRC-026-1302	CACRC-036-1802
CACRC-007-0401	CACRC-017-0901	CACRC-027-1401	CACRC-037-1901
CACRC-008-0402	CACRC-018-0902	CACRC-028-1401	CACRC-038-1902
CACRC-009-0501	CACRC-019-1001	CACRC-029-1501	CACRC-039-2001
CACRC-010-0502	CACRC-020-1002	CACRC-030-1502	CACRC-040-2002

Core supplied in 36 x 98-inch sheets, as shown in figures 5 and 6, was inspected prior to cutting. The core dimensions were first verified (36 x 98 inches), then the core was inspected for cell tearout, core-surface depressions, partial node bond separation, complete node bond separation, or

split/cracked cell walls. All defects found were recorded. Core inspection checklists were used for core inspection and core defect documentation. The core sheets were then cut into two 36 x 48-inch pieces and stored in sealed bags until lay-up. The core ribbon direction was along the 36-inch dimension. Corfil 658 compound was used to pot the core areas corresponding to the repair-element loading and support points, as shown in figure 7. Uncured facesheet 1 was assembled with film adhesive and core, as shown in figures 8–10. This is referred to as assembly 1. Facesheet 1 was cured against the tool surface.

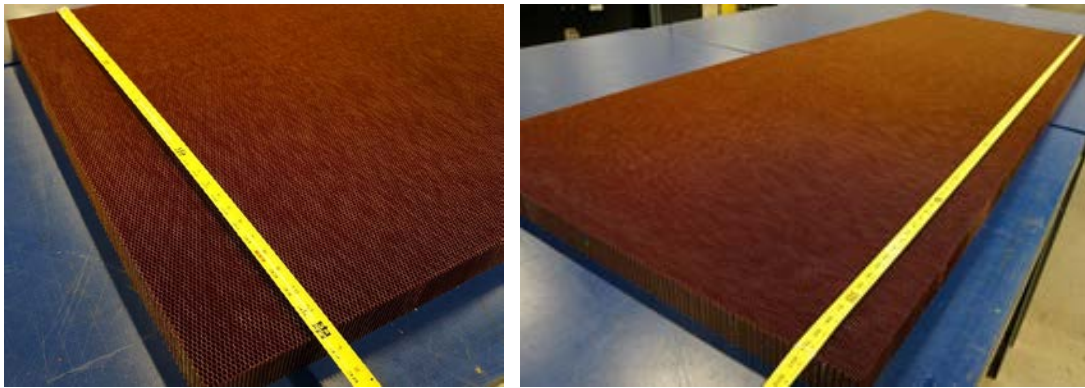


Figure 5. Core sheet 36 x 98 inches, as delivered (ribbon direction along 36-inch width)



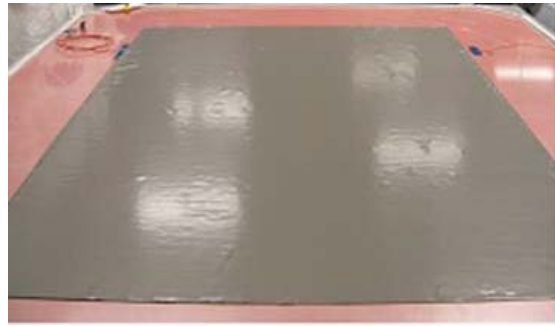
Figure 6. Core preparation for cutting



Figure 7. Potting compound application onto core



(a)



(b)

Figure 8. Facesheet (a) 1 lay-up and (b) adhesive application

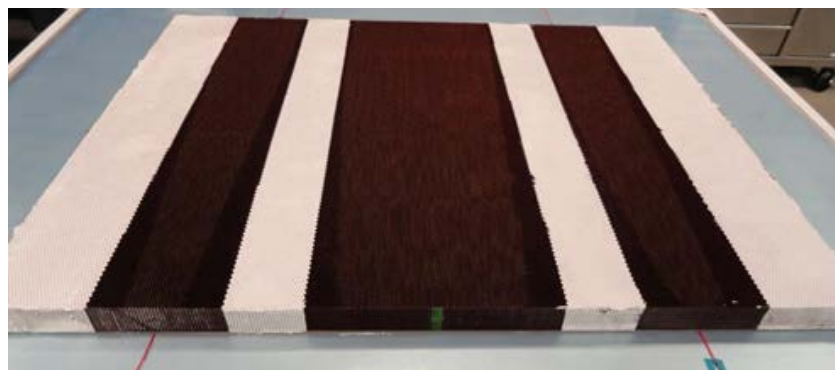


Figure 9. Uncured assembly 1 (facesheet 1, film adhesive and filled core)

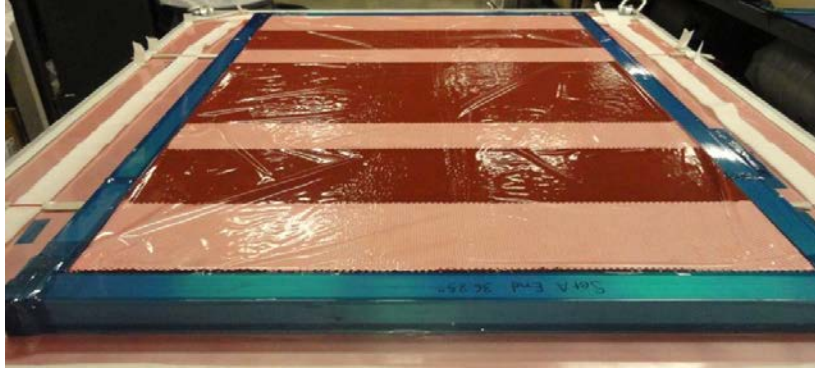


Figure 10. Assembly 1 bagging and preparation for cure

Uncured facesheet 2 was assembled with uncured film adhesive and assembly 1, as shown in figures 11–13. This was the final panel assembly, also cured with facesheet 2 against the tool side, using the same cure cycle as shown in figure 4.



Figure 11. Cured assembly 1 prepared for final assembly



Figure 12. Final assembly (cured assembly 1 and uncured facesheet 2)

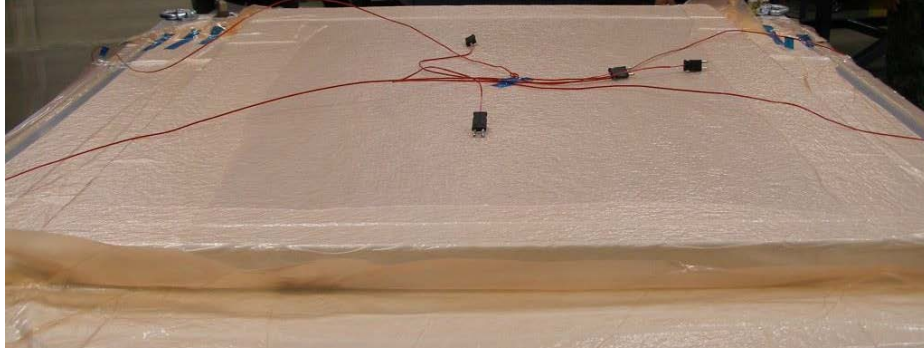


Figure 13. Final assembly/CACRC -001-0101 panel

3.2 SPECIMEN PREPARATION

All panels manufactured per table 3 were machined into three large 11.5 x 48-inch beams, as shown in figures 14–16, and subsequently conformed by NIAR QA personnel, as shown in table 5.

Table 5. Coupon conformity list

Panel ID	Coupon ID	Panel ID	Coupon ID
CACRC-001-0101	CACRC-001-0101-01 thru 03	CACRC-021-1101	CACRC-021-1101-01 thru 03
CACRC-002-0102	CACRC-002-0102-01 thru 03	CACRC-022-1102	CACRC-022-1102-01 thru 03
CACRC-003-0201	CACRC-003-0201-01 thru 03	CACRC-023-1201	CACRC-023-1201-01 thru 03
CACRC-004-0202	CACRC-004-0202-01 thru 03	CACRC-024-1202	CACRC-024-1202-01 thru 03
CACRC-005-0301	CACRC-005-0301-01 thru 03	CACRC-025-1301	CACRC-025-1301-01 thru 03
CACRC-006-0302	CACRC-006-0302-01 thru 03	CACRC-026-1302	CACRC-026-1302-01 thru 03
CACRC-007-0401	CACRC-007-0401-01 thru 03	CACRC-027-1401	CACRC-027-1401-01 thru 03
CACRC-008-0402	CACRC-008-0402-01 thru 03	CACRC-028-1401	CACRC-028-1401-01 thru 03
CACRC-009-0501	CACRC-009-0501-01 thru 03	CACRC-029-1501	CACRC-029-1501-01 thru 03
CACRC-010-0502	CACRC-010-0502-01 thru 03	CACRC-030-1502	CACRC-030-1502-01 thru 03
CACRC-011-0601	CACRC-011-0601-01 thru 03	CACRC-031-1601	CACRC-031-1601-01 thru 03
CACRC-012-0602	CACRC-012-0602-01 thru 03	CACRC-032-1602	CACRC-032-1602-01 thru 03
CACRC-013-0701	CACRC-013-0701-01 thru 03	CACRC-033-1701	CACRC-033-1701-01 thru 03
CACRC-014-0702	CACRC-014-0702-01 thru 03	CACRC-034-1702	CACRC-034-1702-01 thru 03
CACRC-015-0801	CACRC-015-0801-01 thru 03	CACRC-035-1801	CACRC-035-1801-01 thru 03
CACRC-016-0802	CACRC-016-0802-01 thru 03	CACRC-036-1802	CACRC-036-1802-01 thru 03
CACRC-017-0901	CACRC-017-0901-01 thru 03	CACRC-037-1901	CACRC-037-1901-01 thru 03
CACRC-018-0902	CACRC-018-0902-01 thru 03	CACRC-038-1902	CACRC-038-1902-01 thru 03
CACRC-019-1001	CACRC-019-1001-01 thru 03	CACRC-039-2001	CACRC-039-2001-01 thru 03
CACRC-020-1002	CACRC-020-1002-01 thru 03	CACRC-040-2002	CACRC-040-2002-01 thru 03

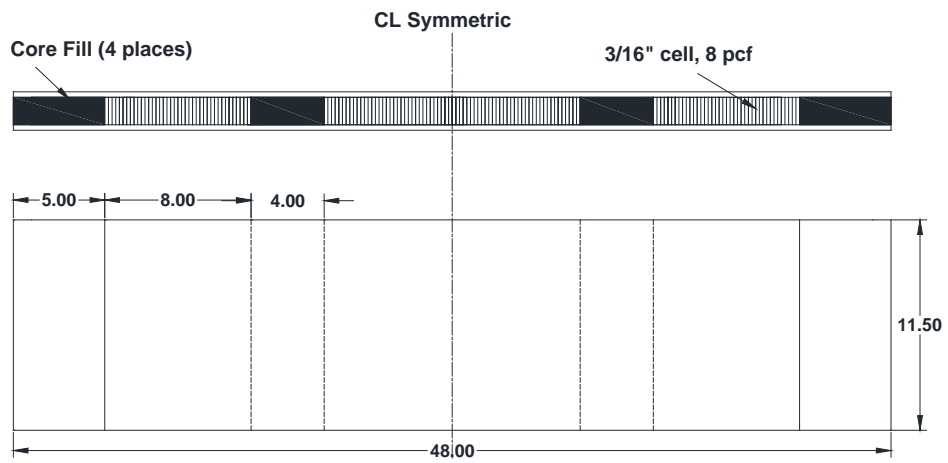


Figure 14. Large-beam drawing

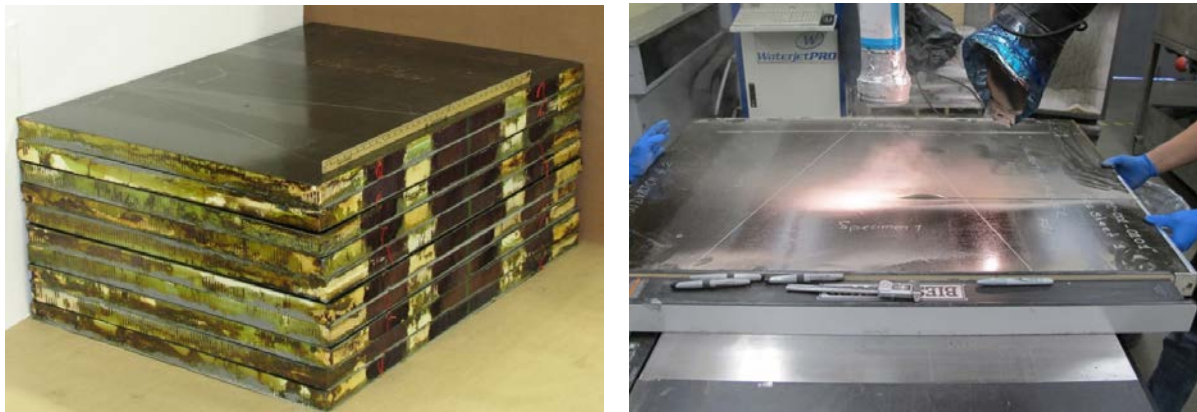


Figure 15. Large-beam machining



Figure 16. Machined elements prior to repair

3.3 CACRC ROUND ROBIN TEST MATRIX

The large-beam repair element used for the round robin exercise is shown in figure 17. The element was 11.5 x 48 inches with 4-ply facesheets, reinforced 8 pcf, 2-inch-thick core under the loading, and support points to prevent core crushing. The parent facesheet material was T300/934 3K PW bonded to the core using FM 377S adhesive.

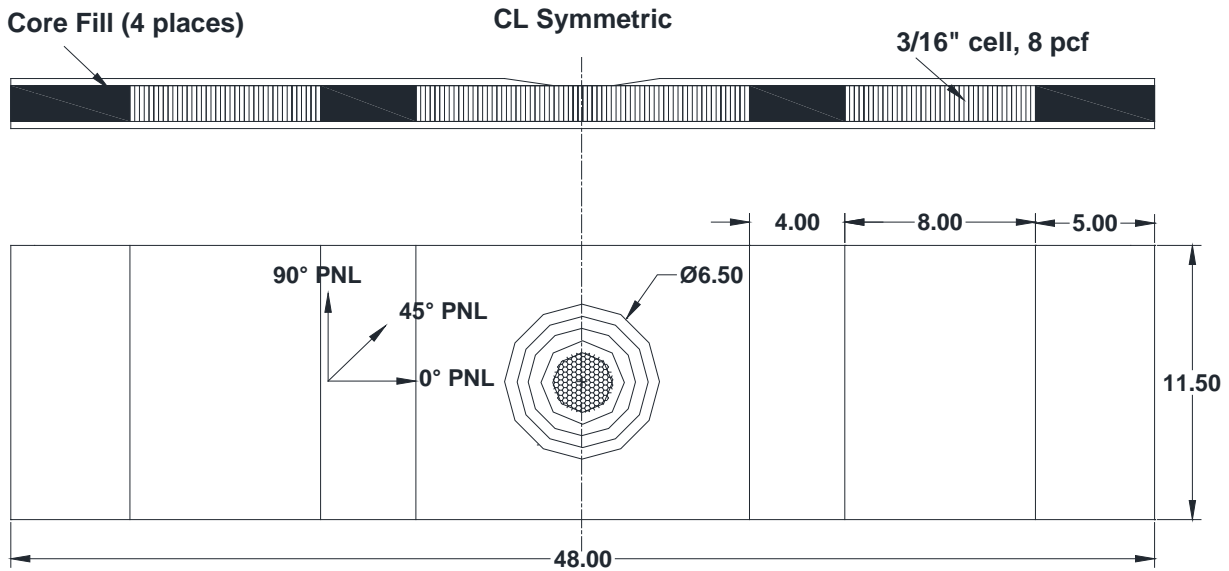


Figure 17. Large-beam configuration

The test matrix used for this research is summarized in table 6. All materials were supplied by the OEM, and all panel fabrication was conducted at the NIAR/NCAT facility using OEM-approved processes to ensure that the resulting repair elements were representative of production materials and processes. Four repair systems were considered: an OEM repair system using the parent material and adhesive for repair (350°F cure repair, labeled as OEM-R1), a wet lay-up repair system using T300 3K fabric with EA9396 C2 laminating resin and EA9696 adhesive (labeled as OEM-R2), and two CACRC field-repair systems using Hexcel M20/G904 prepreg and EA9695 NW adhesive (250°F cure repair, labeled as CACRC-R1) and G904 D1070 TCT fabric with Epocast 52A/B (200°F cure repair, wet lay-up, labeled as CACRC-R2). These repairs were compared to baseline pristine (unrepaired) elements and unrepaired elements scarfed with a 2.5-inch hole diameter. Repairs were conducted at the OEM, NIAR, and five operator depots/Maintenance and Repair Organizations (MRO). The OEM-R1 repairs were performed with T300/934 PW material and FM377 adhesive by OEM-experienced mechanics at the factory.

Three sets of repairs were conducted at NIAR:

1. OEM-R2 repairs using T300 3K fabric with EA9396 C2 laminating resin and EA9696 adhesive
2. CACRC-R1 repairs using Hexcel M20/G904 prepreg and EA9695 NW adhesive
3. CACRC-R2 repairs using G904 D1070 TCT fabric with Epocast 52A/B laminating resin

All depot repairs were conducted using CACRC-R1 (Hexcel M20/G904 prepreg and EA9695 NW adhesive) or CACRC-R2 (G904 D1070 TCT fabric with Epocast 52A/B) materials. With the exception of the three pristine elements tested at room temperature ambient (RTA) to establish the base structure/configuration undamaged strength, all static and fatigue elements were tested at an elevated temperature wet (ETW) condition of 180°F, after moisture conditioning of 145°F, and 85% relative humidity (RH).

Table 6. CACRC round robin test matrix

Repair Station	Element Configuration	Repair Material	Loading Mode	Experience Level	Static RTA	Static ETW	Fatigue ETW
N/A N/A	Pristine/Undamaged Unrepaired/2.5" hole/Scarf	N/A N/A	Compression Compression		3	3 3	3
OEM OEM	Repair/205" hole/0.25" scarf overlap Repair/2.5" hole/0.5" scarf overlap	OEM-R1 OEM-R1	Compression Compression	M2 M2		3 2	3
NIAR NIAR	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	OEM-R2 OEM-R2	Compression Tension	M2 M2		3 3	3 3
NIAR NIAR	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R1	Compression Tension	M2 M2		3 3	3 3
NIAR NIAR	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R2 CACRC-R2	Compression Tension	M2 M2		3 3	3 3
Field Station 1 Field Station 1	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M1 M1		3 3	
Field Station 1 Field Station 1	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M2 M2		3 3	
Field Station 2 Field Station 2	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M1 M1		3 3	
Field Station 2 Field Station 2	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M2 M2		3 3	
Field Station 3 Field Station 3	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M1 M1		3 3	
Field Station 3 Field Station 3	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M2 M2		3 3	
Field Station 4 Field Station 4	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M1 M1		3 3	
Field Station 4 Field Station 4	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M2 M2		3 3	
Field Station 5 Field Station 5	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M1 M1		3 3	
Field Station 5 Field Station 5	Repair/2.5" hole/0.5" scarf overlap Repair/2.5" hole/0.5" scarf overlap	CACRC-R1 CACRC-R2	Compression Compression	M2 M2		3 3	

A detailed repair procedure referencing the relevant SAE CACRC standards was drafted and reviewed by FAA technical monitors, industry points of contact, and all participating OEM and airline depots before performing repairs. The same procedures were used by all participating airline depots to conduct repairs. Detailed repair checklists containing part-specific information along with the CACRC standards were provided to the depot mechanics. Half of the repairs were conducted by mechanics with minimal experience and the other half by experienced mechanics.

Repair kits containing the CACRC repair materials were prepared and shipped to all participating depots as shown in figure 18. The CACRC materials used for repair were Hexcel M20/G904 prepreg with EA9695 NW film adhesive per SAE AMS 3970 [13–17] and Hexcel G904 D1070 TCT PW dry fabric, 193 g/m² using Tenax® Fibers and Huntsmann Epocast 52A/B resin per AMS 2980 [18–23]. Peel ply and perforated film for wet lay-up bagging were also provided to the depots to control the material process variability.

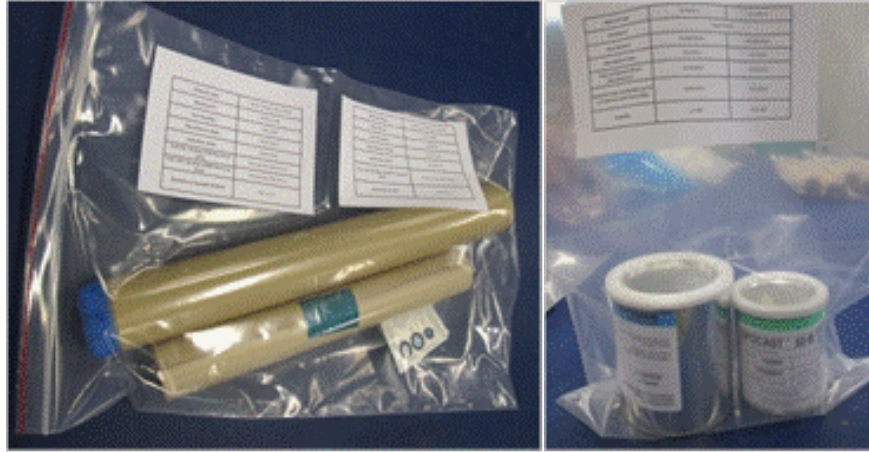


Figure 18. CACRC prepreg and wet lay-up repair materials

3.4 SPECIMEN DESIGN VALIDATION

CACRC-002-0102 panel was used for specimen-design validation and verification. Three sandwich elements were machined and tested at room temperature, and the experimental results are summarized in table 7 . The sandwich beams were instrumented using seven strain gauges to monitor strain distribution during loading. Compression failures were observed for all three elements with a corresponding average ultimate strain of 9340 microstrain (strain gauge 6) consistent with predictions, as shown in figure 19. Strain gauge 6 was located at the center of the beam, and all strain gauges were placed on the upper facesheet, in compression, with the exception of strain gauges 2 and 4, tested in tension.

Table 7. Pristine (undamaged) specimen strength (RTA)

Specimen ID	T [in]	W [in]	L [in]	L _s [in]	L _L [in]	F _U [lbs]	Def _U [in]	σ _c [ksi]	S ₁ [μΕ]	S ₂ [μΕ]	S ₃ [μΕ]	S ₄ [μΕ]	S ₅ [μΕ]	S ₆ [μΕ]	S ₇ [μΕ]
CACRC-002-0102-001-B-RTA-1	2.1	11.6	47.8	42	18	7269	1.791	56.5	9,699	8801	9428	8662	9480	9653	9,915
CACRC-002-0102-001-B-RTA-2	2.1	11.9	47.8	42	18	7349	1.765	55.8	9277	8669	9485	8520	9914	9653	9,293
CACRC-002-0102-001-B-RTA-3	2.1	11.3	47.8	42	18	6520	1.655	52.2	8538	7981	8652	8297	8812	8713	8,620
Average	2.1	11.6	47.8	42	18	7046	1.737	54.8	9171	8484	9188	8493	9402	9340	9,276
Standard Deviation						457	0.072	2	588	440	465	184	555	543	648
Coefficient of Variation %						6.5	4.2	4.2	6.4	5.2	5.1	2.2	5.9	5.8	7.0



Figure 19. CACRC round robin baseline specimen-failure modes

3.5 REPAIR PROCEDURES

3.5.1 CACRC R1 Prepreg Repair Procedure

A detailed repair procedure referencing the relevant SAE CACRC standards was drafted and reviewed by all sponsors and used by all participating airline depots to conduct the repairs. Detailed repair checklists containing part-specific information along with the CACRC standards were provided to the depot mechanics. Repair kits containing the CACRC repair materials were prepared and shipped to all participating depots. Peel ply and perforated film for wet lay-up bagging were also provided to the depots to control the material process variability. It should be noted that the CACRC prepreg material system had long lead times and was hard to procure, especially in small quantities. It should also be stressed that the CACRC materials are not commonly called out in today's SRM.

Four repair configurations/types were evaluated as part of the CACRC round robin testing. This section outlines the repair procedures for CACRC-R1—a prepreg repair using CACRC-approved repair materials per AMS 3970 [13–17].

Repair materials
Hexcel M20/G904 prepreg
EA9695 NW 0.05 psf film adhesive

Repair procedure

1. Thaw the repair kit from 0°F (-17.8°C) to room temperature for at least 10 hours prior to bonding the repair. The kit supplied is contained in a sealed moisture proof bag and should be stored at or below 0°F (-17.8°C). The storage life for this repair system (prepreg and adhesive) is 12 months from the date of shipment and the out time is 10 days at RTA. Please refer to the actual kit out time and shelf life as specified in each package (out time for material handling and kit preparation already accounted for) [17].
2. Inspect the materials contained in the repair kit to ensure that all materials required for repair have been provided. Cut the required adhesive and prepreg plies.
Materials:
 - Hexcel M20/G904 prepreg material (cut the required repair plies 3.5 inches, 4.5 inches, 5.5 inches, and 6.5 inches in diameter)
 - EA9695 NW 0.05 psf film adhesive material (cut two layers of adhesive 7.0 inches in diameter)
 - Seal and store at room temperature until needed for the repair/bonding operations. If the repair is planned for a later date, store in a freezer at or below 0°F (-17.8°C) until needed. Allow 8–10 hours for kit to thaw prior to bonding the repair.
3. Prepare the panel for repair by identifying the panel 0° direction (0° direction is along the panel length). Mark panel (PNL) orientation as 0PNL, 90PNL, 45PNL as shown in figure 20. All repairs must be conducted on facesheet 2 (FS2) of the panels. The panel 0° direction is aligned with the panel's 48-inch length.
4. Mask a 7-inch diameter area at the center of the panel in preparation for scarf sanding. Use the guidelines of ARP 4916 masking methods 4 or 5 using masking tape [24]. Using a Mylar® template (or equivalent), mark the inner 2.5-inch-diameter scarf circle/boundary and the outer 6.5-inch-diameter scarf periphery. Take a photograph of the prepared marked panel ready for sanding, including a 12-inch scale for reference.
5. Scarf sand from an inner diameter of 2.5 inches to an outer diameter of 6.5 inches per AIR 5367 [25] sections 5.0 and 5.1 using a 0.5-inch + 0.25-inch per ply overlap. (Use an air-powered die grinder or equivalent with aluminum-oxide sanding discs for scarf sanding.) Start sanding with 80-grit abrasive paper and finish with 150-grit abrasive paper. Remove the remaining 2.5-inch-diameter center disk after scarf sanding is complete. (The scarf boundary extends from the 2.5-inch inner diameter to the 6.5-inch outer diameter. Using the same procedure, abrade the area extending from the 6.5-inch inner diameter to the 7.0-inch outer diameter.)

WARNING: WHILE SANDING, IT IS MANDATORY TO WEAR PROTECTIVE GLOVES, SAFETY GLASSES, DISPOSABLE LAB COATS, AND DUST MASKS FOR PROPER PROTECTION FROM SKIN CONTACT WITH DUST AND DUST INHALATION

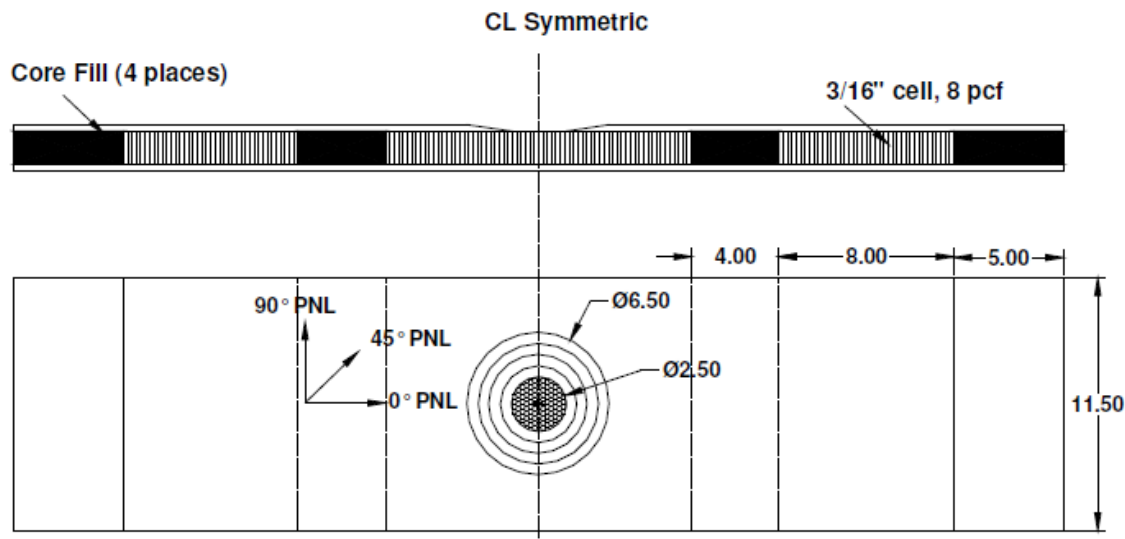


Figure 20. Scarf-sanded panel ready for repair

6. Remove all sanding debris using oil-free compressed filtered air and a vacuum cleaner. Clean per ARP 4916 Method 5 two-cloth method, using approved solvents and wiping media per AMS 3819C [26] that will not leave a residue. Take a photograph of the scarfed cleaned panel.
7. Use a ruler or straight edge to ensure adequate core height with respect to the inner scarf boundary. Use a feeler gauge (or equivalent) to measure the depth of the core with respect to the inner scarf boundary. Use filler plies if the depth of the core is lower than that of the inner-scarf boundary. Do not use more than three filler plies. Record depth and number of filler plies.
8. Mask the core per ARP 4916, and perform the water break test after cleaning using ARP 4916 section 14.1.2.
9. Envelope bag the panel and dry per ARP 4977 [27] section 4.2 at 180°F under vacuum for at least 2 hours. Report the method used for drying.
10. Final clean per ARP 4916 [24] method 5 using approved solvent and wiping media per AMS 3819C Class 1 only. Record the time the final cleaning was completed. Repair application must be conducted 20–30 minutes after final cleaning.

WARNING: A CONTAMINATED OR INADEQUATELY PREPARED SCARFED SURFACE WILL YIELD A DEFECTIVE REPAIR. BE ABSOLUTELY CERTAIN TO REMOVE PREPREG AND ADHESIVE BACKING AND SEPARATOR FILMS. FAILURE TO REMOVE BACKING FILM WILL RESULT IN A DEFECTIVE REPAIR.

11. Layup the repair patch as follows (figure 21 is a representative example):

- Two layers of EA9695 NW 0.05 psf adhesive (7.0-inch diameter)
- Repair ply 1: $[0^\circ/90^\circ]$, 3.5-inch diameter
- Repair ply 2: $[\pm 45^\circ]$, 4.5-inch diameter
- Repair ply 3: $[\pm 45^\circ]$, 5.5-inch diameter
- Repair ply 4: $[0^\circ/90^\circ]$, 6.5-inch diameter
- Take photographs of the adhesive and ply lay-up.

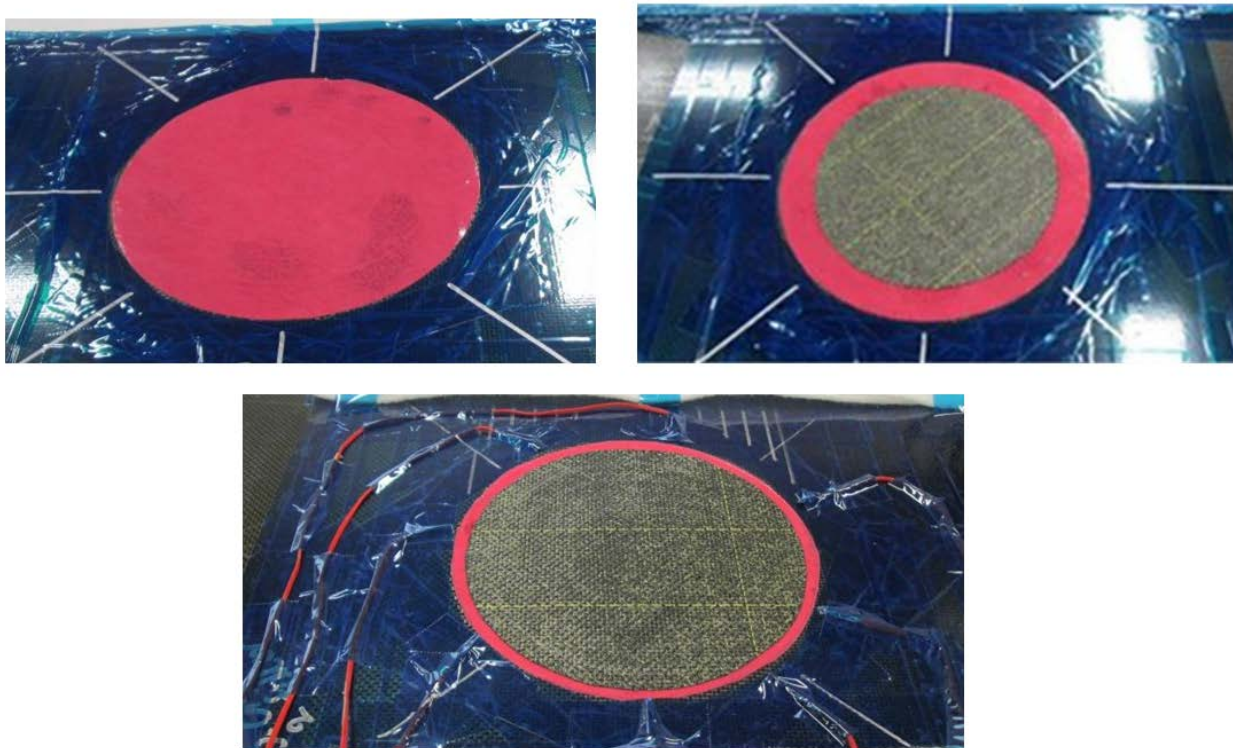


Figure 21. Repair adhesive and ply application

12. Following the guidelines of ARP 4916 method 4 or 5, use masking tape to cover 2-inch periphery around the repair.
13. Install a minimum of eight thermocouples per repair per ARP5144 [28] and envelop bag using the no-bleed method per ARP 5143 [29], as shown in figure 22. For proper heat application, the heat blanket must be larger than the repair area by a minimum of 2 inches on all repair sides. Use a second blanket to heat up the bottom facesheet of the panel. Use three thermocouples to monitor the temperature on the unrepaired facesheet. Perform a

leak test to check the integrity of the bag. The leak rate should not exceed 5 in. Hg in 5min. Record the vacuum leak rate.

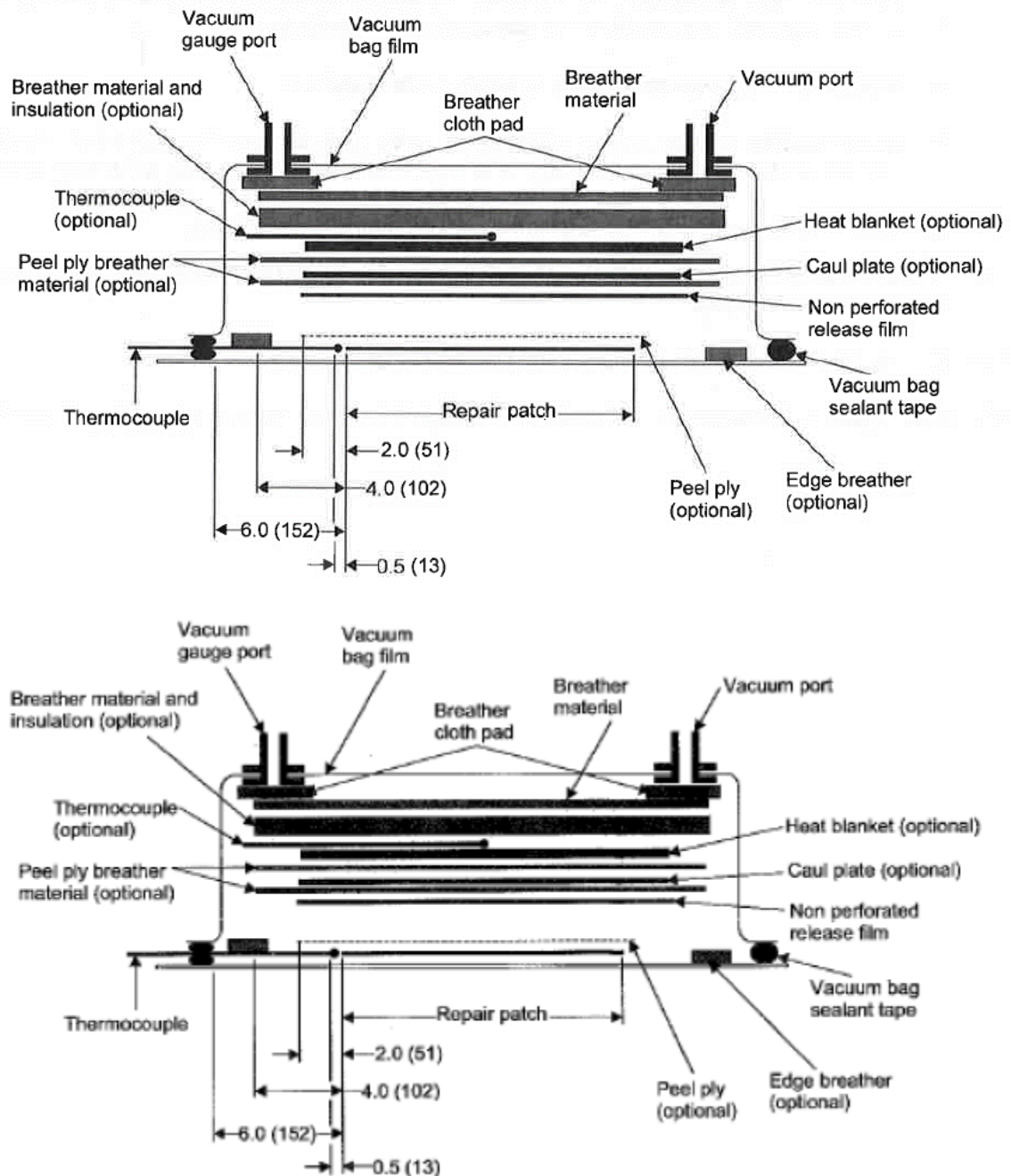


Figure 22. Bagging procedure (no-bleed cure) [29]

Apply heat and cure per ARP 5144. Use two heat blankets for all repairs and ensure that the areas around and above the heat blanket are properly insulated to reduce heat loss. Ensure that the hot-bond vacuum-assisted machine and the thermocouples are calibrated

according to the requirements of ARP 5144. The recommended cure cycle is shown in table 8.

Table 8. Cure cycle for CACRC prepreg repair material

Cure Cycle – CACRC Prepreg Material				
Cure Parameters	Units	Requirements	Units	Requirements
Heating Rate	°C/min	1–3	°F/min	2–5
Cure Temperature	°C	120–130	°F	248–266
Cure Time	min	180–240	min	180–240
Cure Pressure	kpa	>0.75	in-Hg	>21
Cooling Rate	°C/min	5 max	°F/min	9

14. Inspect using tap testing, MIA, PE/through-transmission ultrasonics (TTU), per ARP 5089 [30].

3.5.2 CACRC R2 Wet Lay-Up Repair Procedure

Four repair configurations/types are currently being evaluated as part of the CACRC round robin testing. This section outlines the repair procedures for CACRC-R2, a wet lay-up repair using CACRC-approved repair materials per AMS 2980 [18–23].

Repair materials Hexcel G904 D1070 TCT, PW fabric, 193 g/m² using Tenax Fibers Huntsmann Epocast 52A/B laminating resin

Repair procedure

1. Inspect the materials contained in the wet lay-up repair kit to ensure that all materials required for repair have been provided.

Materials:

- Dry carbon fabric, supplied in a sealed moisture proof bag. The fabric can be stored in a sealed, dry plastic bag for a minimum of 2 years from the manufacture date [19].
 - Epocast 52A/B laminating resin, 1-quart kit supplied. The resin can be stored for 6 months at room temperature. Refer to the actual kit out time and shelf life as specified in each package. (Out time for material handling and kit preparation already accounted for.)
2. Prepare the panel for repair by identifying the panel 0° direction (0° direction is along the panel length). Mark panel orientation as 0PNL, 90PNL, and 45PNL as shown in figure 23. All repairs must be conducted on facesheet 2 (FS2) of the panels. The panel 0° direction is aligned with the panel's 48-inch length.

scarf boundary. Use filler plies if the depth of the core is lower than that of the inner-scarf boundary. Do not use more than three filler plies.

7. Perform the water break test after cleaning using ARP 4916 section 14.1.2.
8. Envelope bag the panel and dry per ARP 4977 [27] at 180°F under vacuum for 2 hours. Report the method used for drying.
9. Final clean per ARP 4916 [24] method 5 using approved solvent and wiping media per AMS 3819C Class 1 only [26]. Record the time the final cleaning was completed. Repair application must be conducted 20–30 minutes after final cleaning.

WARNING: A CONTAMINATED OR INADEQUATELY PREPARED SCARFED SURFACE WILL YIELD A DEFECTIVE REPAIR. BE ABSOLUTELY CERTAIN TO REMOVE PREPREG AND ADHESIVE BACKING AND SEPARATOR FILMS. FAILURE TO REMOVE BACKING FILM WILL RESULT IN A DEFECTIVE REPAIR.

10. To determine the resin weight required, determine the amount of fabric needed based on the number and size of repair plies required (refer to step 11). Account for any additional filler plies, if necessary.
Weigh the fabric and determine the amount of resin required for the repair according to ARP5256. Mix the resin per ARP 5256 [31], as shown in figure 24. The mixing ratio for the Epocast 52 A/B is as follows: to 100 parts by weight of Epocast 52-A, add 41 parts by weight of Epocast 52-B. Record the time the resin mixing is started. Mix both components for 5 minutes until a homogeneous mixture is obtained.



Figure 24. Epocast 52A/B resin mixing

WARNING: THE REPAIR MUST COMPLETED WITHIN 80% OF RESIN POT LIFE TO ENSURE ADEQUATE TIME FOR LAMINATE CONSOLIDATION.

11. Impregnate the repair plies and apply per ARP 5319 [32] section 3.2 using Epocast 52 A/B resin per AMS 2980/4A [22] and TENEX HTA5131200TEXF3000 fiber per AMS 2980/3A [21], as shown in figure 25. Cut the plies and prepare for repair application.

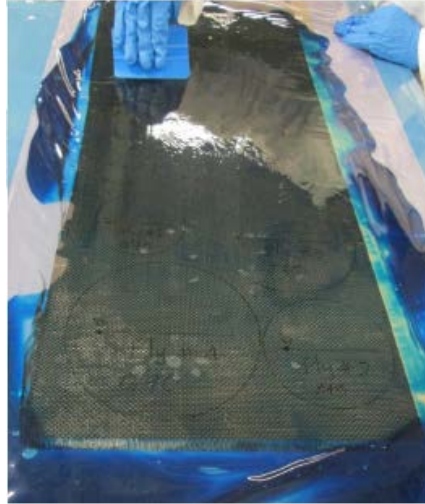


Figure 25. Dry-fiber impregnation with Epocast 52A/B resin

Record the repair start time. Match the parent laminate ply orientations and add one extra ply in the dominant direction.

- Repair ply 1: [0/90], 3.5-inch diameter
 - Repair ply 2: [± 45], 4.5-inch diameter
 - Repair ply 3: [± 45], 5.5-inch diameter
 - Repair ply 4: [0/90], 6.5-inch diameter
 - Repair ply 5: [0/90], 7.5-inch diameter; this is the extra ply
 - Take photographs of the ply lay-up.
12. Following the guidelines of ARP 4916 [24] methods 4 or 5; use masking tape to cover 2-inch periphery around the repair.
 13. Install eight thermocouples per repair per ARP5144 [28] and envelop bag using the vertical bleed method ARP 5143 [29]. Use a second blanket to heat up the bottom facesheet of the panel. Bagging should occur at maximum 80% of the resin pot life. Perform a leak test to check the integrity of the bag; the leak rate should not exceed 5 inches Hg in 5 minutes. Record the vacuum leak rate.
 - Peel ply: Airtech Nylon 62g/m², release ply B.
 - Bleeder: One ply of style 120 glass fabric.
 - Perforated film: Airtech perforated release film P (FEP, hole diameter 1.143mm, 1.27% open area).
 14. Apply heat and cure per ARP 5144. Use two heat blankets for all repairs, and ensure that the areas around and above the heat blanket are properly insulated to reduce heat loss. Ensure that the hot-bond vacuum-assisted machine and the thermocouples are calibrated according to the requirements of ARP 5144. The recommended cure cycle is shown in table 9.

Table 9. Cure cycle for CACRC wet lay-up repair material

Cure Cycle – CACRC Wet Lay-Up Material				
Cure Parameters	Units	Requirements	Units	Requirements
Heating Rate	°C/min	1–3	°F/min	2–5
Cure Temperature	°C	93°–103°	°F	200°F–217°F
Cure Time	min	120–180 min	min	120–180 min
Cure Pressure	bar	>0.75	in-Hg	>22
Cooling Rate	°C/min	5 max	°F/min	9 max

15. Inspect using tap testing, MIA, and PE/TTU per ARP 5089 [30].

3.5.3 OEM R1 Prepreg Repair Procedure

This section outlines the repair procedures for OEM-R1, a prepreg repair using OEM-approved repair materials.

Repair materials

Cytec T300/934 3K PW fabric, 193 g/m²

Cytec FM377S 0.08 PSF

Repair procedure

All OEM-R1 repairs were conducted at the factory by OEM mechanics using the same parent material for repair and a proprietary process to consolidate and cure the repair patch using a heat blanket under vacuum (no autoclave pressure).

3.5.4 OEM R2 Wet Lay-Up Repair Procedure

This section outlines the repair procedures for OEM-R2, a wet lay-up repair using OEM-approved repair materials.

Repair materials

Cytec T300 3K PW fabric, 193 g/m²

Hysol EA9396 C2

Hysol EA 9696NW 0.06 psf

Repair procedure:

1. Inspect the materials contained in the wet lay-up repair kit to ensure that all materials required for repair have been provided.

Materials:

Dry carbon fabric, supplied in a sealed moisture-proof bag. The fabric can be stored in a sealed dry plastic bag for a minimum of 2 years from the manufacture date. Hysol EA9396 C2 structural adhesive (1-quart kit supplied) can be stored for 1 year at room temperature.

EA9696 film adhesive (supplied in a sealed, moisture-proof bag) has a shelf life of 12 months from the date of shipment and a 60-day out time at room temperature. Refer to the actual kit out time and shelf life as specified in each package. (Out time for material handling and kit preparation is already accounted for.)

2. Prepare the panel for repair by identifying the panel 0° direction (0° direction is along the panel length). Mark panel orientation as 0PNL, 90PNL, and 45PNL, as shown in figure 23. All repairs must be conducted on facesheet 2 (FS2) of the panels. The panel 0° direction is aligned with the panel's 48-inch length.
3. Mask an 8-inch-diameter area at the center of the panel in preparation for scarf sanding. Use the guidelines of ARP 4916 methods 4 or 5 using masking tape [24]. Using a Mylar template (or equivalent), mark the inner 2.5-inch-diameter scarf circle/boundary and the outer 6.5-inch-diameter scarf periphery. Take a photograph of the prepared marked panel ready for sanding, including a 12-inch scale for reference.
4. Scarf sand from an inner diameter of 2.5 inches to an outer diameter of 6.5 inches per AIR 5367 [25] sections 5.0 and 5.1 using a 0.5-inch-per-ply overlap. Use an air-powered die grinder, or equivalent, with aluminum oxide sanding discs for scarf sanding. Start sanding with 80-grit abrasive paper and finish with 150-grit abrasive paper. Remove the remaining 2.5-inch diameter center disk after scarf sanding is complete.

(The scarf boundary extends from the 2.5-inch inner diameter to the 6.5-inch outer diameter. Using the same procedure, abrade the area extending from the 6.5-inch inner diameter to the 7.75-inch outer diameter)

WARNING: WHILE SANDING, IT IS MANDATORY TO WEAR PROTECTIVE GLOVES, SAFETY GLASSES, DISPOSABLE LAB COATS, AND DUST MASKS FOR PROPER PROTECTION FROM SKIN CONTACT WITH DUST AND DUST INHALATION

5. Remove all sanding debris using oil-free compressed filtered air and a vacuum cleaner. Clean per ARP 4916 [24] method 5 two-cloth method, using approved solvents and wiping media per AMS 3819C [26] that will not leave a residue. Take a photograph of the scarfed, cleaned panel.
6. Use a ruler or straight edge to ensure adequate core height with respect to the inner-scarf boundary. Use a feeler gauge to measure the depth of the core with respect to the inner scarf boundary. Use filler plies if the depth of the core is lower than that of the inner-scarf boundary. Do not use more than three filler plies.
7. Perform the water break test after cleaning, using ARP 4916 section 14.1.2.
8. Envelope bag the panel and dry per ARP 4977 [27] at 180°F under vacuum for at least 2 hours.

9. Final clean per ARP 4916 [24] method 5 approved solvents and wiping media per AMS 3819C Class 1 only [26]. Record the time the final cleaning was completed. Repair application must be conducted 20–30 minutes after final cleaning.

WARNING: A CONTAMINATED OR INADEQUATELY PREPARED SCARFED SURFACE WILL YIELD A DEFECTIVE REPAIR. BE ABSOLUTELY CERTAIN TO REMOVE PREPREG AND ADHESIVE BACKING AND SEPARATOR FILMS. FAILURE TO REMOVE BACKING FILM WILL RESULT IN A DEFECTIVE REPAIR.

10. To determine the resin weight required, determine the amount of fabric needed based on the number and size of repair plies required (refer to step 11). Account for any additional filler plies, if necessary. Weigh the fabric and determine the amount of resin required for the repair according to ARP5256. Mix the resin per ARP 5256 [31]. The mixing ratio for the EA 9396 C2 is as follows: to 100 parts by weight of part A, add 36 parts by weight of EA 9396 C2 part B. Record the time resin mixing is started. Mix both components for 5 minutes until a homogeneous mixture is obtained.

WARNING: THE REPAIR MUST BE COMPLETED WITHIN 80% OF RESIN POT LIFE TO ENSURE ADEQUATE TIME FOR LAMINATE CONSOLIDATION.

11. Impregnate the repair plies and apply per ARP 5319 [32] section 3.2 using EA9396C2 and Cytec T300 3K PW fabric, 193 g/m². Cut the plies and prepare for repair application. Record the repair start time. Match the parent laminate ply orientations and add one extra ply in the dominant direction. Apply one layer of EA9696 film adhesive 7.75 inches in diameter first before applying the repair plies.
- Repair ply 1: [0/90], 3.5-inch diameter
 - Repair ply 2: [\pm 45], 4.5-inch diameter
 - Repair ply 3: [\pm 45], 5.5-inch diameter
 - Repair ply 4: [0/90], 6.5-inch diameter
 - Repair ply 5: [0/90], 7.5-inch diameter (this is the extra ply)
 - Take photographs of the ply lay-up.
12. Following the guidelines of ARP 4916 methods 4 or 5, use masking tape [24] to cover the 2-inch periphery around the repair.
- Install eight thermocouples per repair per ARP5144 [28] and envelop bag using the vertical bleed method per ARP 5143 [29]. Use a second blanket to heat up the bottom facesheet of the panel and install three thermocouples on the unrepaired facesheet. Bagging should occur at maximum 80% of the resin pot life. Perform a leak test to check the integrity of the bag. The leak rate should not exceed 5 in. Hg in 5 min. Record the vacuum leak rate.
 - Peel ply: Airtech Nylon 62g/m², release ply B.
 - Bleeder: One ply of style 120 glass fabric.
 - Perforated film: Airtech perforated release film P (FEP, hole diameter 1.143mm, 1.27% open area).

13. Apply heat and cure per ARP 5144. Use two heat blankets for all repairs and ensure that the areas around and above the heat blanket are properly insulated to reduce heat loss. Ensure that the hot bond vacuum-assisted machine and the thermocouples are calibrated according to the requirements of ARP 5144. The recommended cure cycle is shown in table 10).

Table 10. Cure cycle for CACRC OEM wet lay-up repair material

Cure Cycle – CACRC OEM Wet Lay-Up Material		
Cure Parameters	Requirements (SI)	Requirements (EN)
Heating Rate	1–3°C/min	2–5°F/min
Cure Temperature	123°C–130°C	255°F–265°F
Cure Time	60–90 min	60–90 min
Cure Pressure	>0.75 bar	>22 inches Hg
Cooling Rate	(5°C/min) max	(9°F/min) max

14. Inspect using tap testing, MIA, PE/TTU per ARP 5089 [30].

3.6 CACRC DEPOT MECHANIC SURVEY RESULTS SUMMARY

A total of 16 depot mechanics participated in the study, performing the repairs, participating in the CACRC surveys, or both. Preliminary data gathered are summarized in table 11, which provides information on the mechanics' formal and on-the-job training (OJT), years of experience, and estimated number of repairs performed during that time. These data were self-reported by each mechanic. Seventy-five percent of the mechanics who participated in the survey have an airframe or an airframe and power plant license and all mechanics received OJT.

Table 11. CACRC depot mechanic survey responses

Participants	Company Certification/ Qualification Program	Years of Experience	Number of Repairs Performed
Mechanic 1	OJT, OEM fiberglass class, worked on metals initially then composites	23 years working on AOG	~5000 repairs, 60% wet lay-up, 40% prepreg repairs
Mechanic 2	OJT, operator basic course	Minimal	Underdog Training
Mechanic 3	OJT, operator basic course	16 years of experience with composites	~700 repairs, 40% wet lay-up, 60% prepreg repairs
Mechanic 4	OJT, operator composite classes	15 years of experience in composites	~1700 repairs, 50% wet lay-up repairs, 50% prepreg repairs
Mechanic 5	OJT, 2 classes 1 week each Basic composites I/II	3 years in composites	~500 repairs performed, 60% wet lay-up repairs, 40% prepreg repairs
Mechanic 6	OJT, operator basic composite course (40 hours), advanced course (40 hours), OEM composite class (120 hours)	20 years of experience working on composites	~4000 repairs completed, 67% wet lay-up, 33% prepreg repairs
Mechanic 7	OJT, operator general composites course (3 days) and advanced composites course (5 days)	24 years in composites	~2500 repairs, 10% wet lay-up, 90% prepreg repairs
Mechanic 8	OJT, operator basic course (5 days), advanced course (5 days), advanced composites hands-on course (1 week)	13 years in composites	~3500 repairs, 50% wet lay-up repairs, 50% prepreg repairs
Mechanic 9	OJT	10 years in aircraft industry, 3.5 years in composites early in career	~72 repairs, more than 95% wet lay-up repairs

Table 11. CACRC depot mechanic survey responses (continued)

Participants	Company Certification/ Qualification Program	Years of Experience	Number of Repairs Performed
Mechanic 10	OJT	2 years of composite experience	~310 repairs more than 95% wet lay- up repairs
Mechanic 11	OJT	3 years of composite experience	~780 repairs
Mechanic 12	OJT	20 years of experience, 10 years of composite experience	~2000 repairs
Mechanic 13	OJT	24 years of experience in aviation, 15 years of experience in composites	~1800 repairs, 45% wet lay-up, 55% prepreg repairs
Mechanic 14	OJT	22 years of experience in aviation, 7 years of experience in composites	
Mechanic 15	OJT, operator 1-week course, 2-week composite tooling course	18 years of experience in composites	~3000 repairs, 60% wet lay-up repair, 40% prepreg repairs
Mechanic 16	OJT, operator 2-week course, OEM basic repair course	27 years of experience in aviation, 14 years of experience in composites	~1100 repairs

The CACRC standards were provided to the repair mechanics along with repair checklists for each of the repaired beams. The checklists provided contained part-specific information such as stacking sequence and material details, and provided step-by-step instructions for repair following the relevant CACRC standards. The checklists referenced the CACRC repair techniques for panel masking, taper sanding, part masking, solvent cleaning, bagging, drying, thermocouple installation, curing, etc.

The CACRC standards cannot be used as a sole document to repair a composite part. A part-specific document with the relevant part information is also required, such as a part-specific SRM. The standards are intended to provide best practices for specific operations and not replace repair documents. Some of the CACRC standards were difficult to interpret and had missing or incomplete information, and outdated or unfamiliar nomenclature (“mushroom sanding disk holder”). Several participants had difficulties with the resin-mixing ratios in ARP 5256.

From the surveys conducted and discussions with depot personnel, there was a general consensus on the importance of training with composite materials and repairs for a better understanding of the repair process to produce more effective and repeatable repairs and to minimize rework. There was also an agreement on the need for repair material and procedure standardization and teamwork between engineers, mechanics, and inspectors. More accessibility to engineering documentation and data, training with OEM documents and SRM, and training to a particular repair manual are needed because of the differences between various OEM repair manuals and repair manuals used for different parts.

Depot personnel may spend years becoming familiar with a particular SRM. Most of the time spent preparing for a repair is used to interpret the SRM, search for materials, and prepare the tooling required. Performing the repair itself takes a fraction of the total time. It should be noted that many repairs are performed on similar parts at an OEM, but at an airline depot, a mechanic may only repair a given part occasionally, so practice and training is needed on the same part. In addition, repairs must be performed within a given timeframe in a depot, such as in the case of aircraft on the ground. Continuity from shift to shift and the importance of working on projects from start to finish was another topic brought up by depot personnel during surveys.

There was an overall consensus that the existing training classes are too broad and not specific enough, and that more in-depth training is required. Some recommended training topics might include an overview of the history of composites in airframe structures; an overview of composite fundamentals, such as materials, handling and storage, manufacturing and repair techniques; composite part identification (know what to look for, material type, style); and working and training on example parts. Other topics include computer training for depot personnel to access SRM and find required documentation, composite part identification, understanding the differences between different repairs (such as wet lay-up and prepreg), and the importance of following the repair process. Training should incorporate examples of process deviations and the potential safety implications if bad processes are followed. The surveys underscored the importance of in-depth training of composite repair technicians and the need for periodic training and certification validation.

3.7 CACRC DEPOT AND OEM REPAIRS PROCESS SUMMARY

Figures 26–30 show the repairs conducted at the various depots. Figure 26 provides an overview of a wet lay-up repair conducted at depot 1 following the same procedure provided to all depots. The figure shows the scarfing process, the wet lay-up repair ply impregnation, and lay-up.

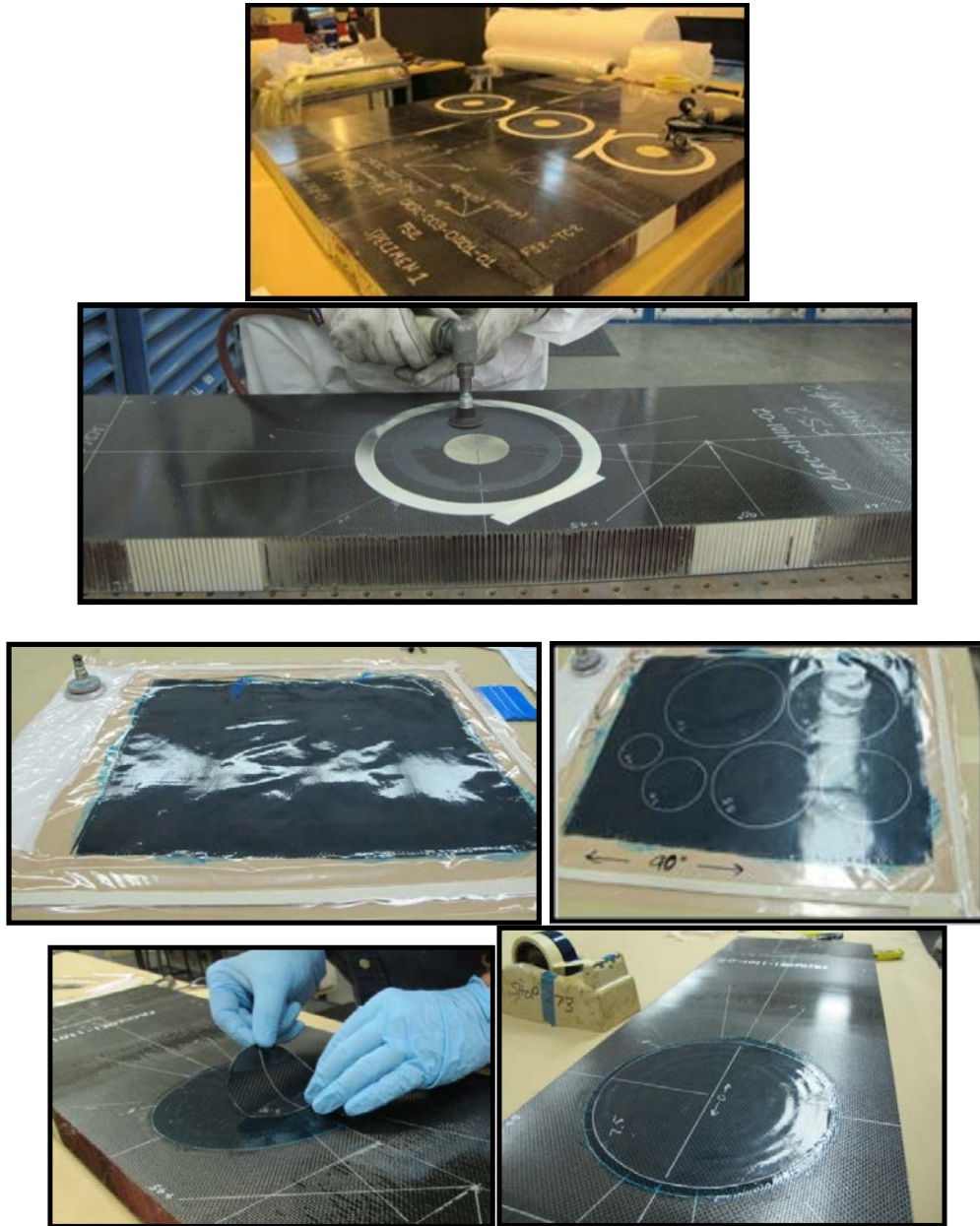


Figure 26. CACRC wet lay-up repair conducted at depot 1

Figure 27 provides an overview of a prepreg repair conducted at depot 2 following the same procedure provided to all depots. The figure shows the scarfing process, the prepreg repair ply preparation, cutting, repair, and the final cured prepreg repair. It should be noted that the first ply was over-sanded during the scarfing process, as shown in the figure. This exemplifies realistic

damage scenarios that may occur during damage removal and parent substrate scarfing, regardless of the level of training or competency of the repair technician performing the composite repair.

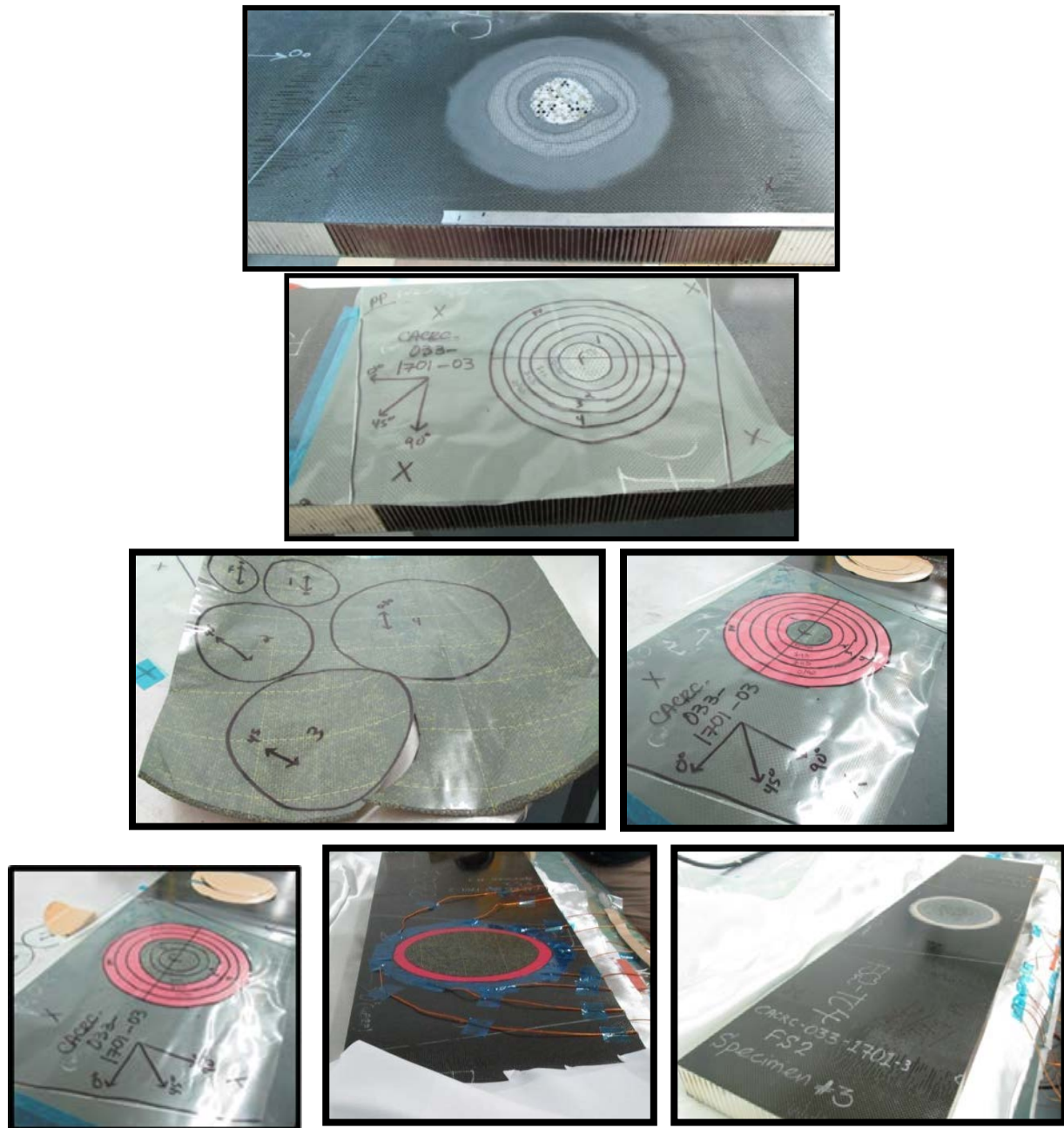


Figure 27. CACRC prepreg repair conducted at depot 2

Figure 28 provides an overview of a wet lay-up repair conducted at depot 3 following the same procedure provided to all depots. The figure shows the scarfing process, the wet lay-up repair ply impregnation and lay-up, and the heat-blanket application in preparation for curing.



Figure 28. CACRC wet lay-up repairs conducted at depot 3

Figure 29 provides an overview of a wet lay-up repair conducted at depot 4 following the same procedure provided to all depots. The figure shows the scarfing process, the panel drying prior to repair, and the wet lay-up repair ply impregnation and lay-up.

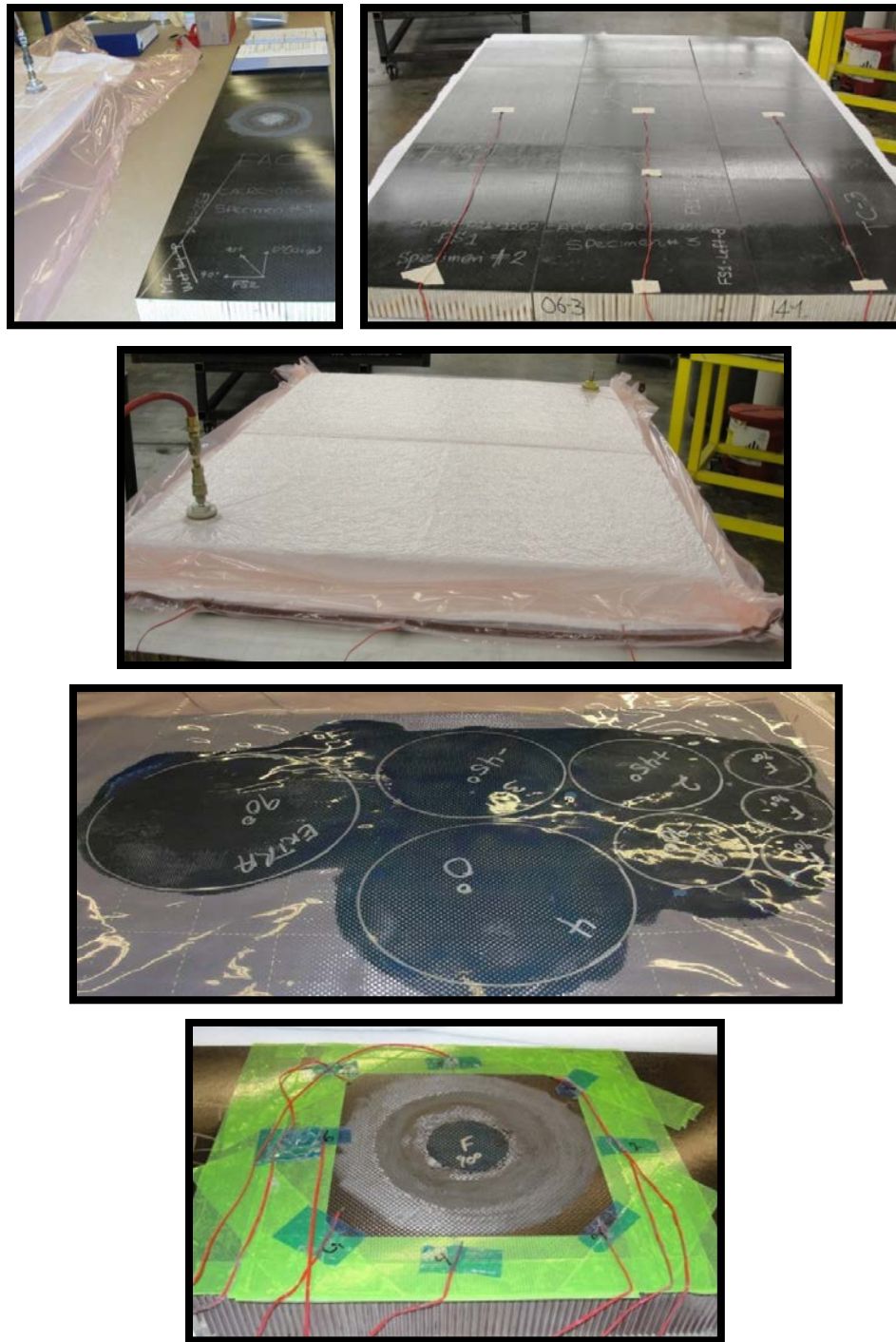


Figure 29. CACRC wet lay-up repairs conducted at depot 4

Figure 30 provides an overview of prepreg repairs conducted at depot 5 following the same procedure provided to all depots. The figure shows the scarfing process, the repair lay-up, and heat-blanket application prior to cure.

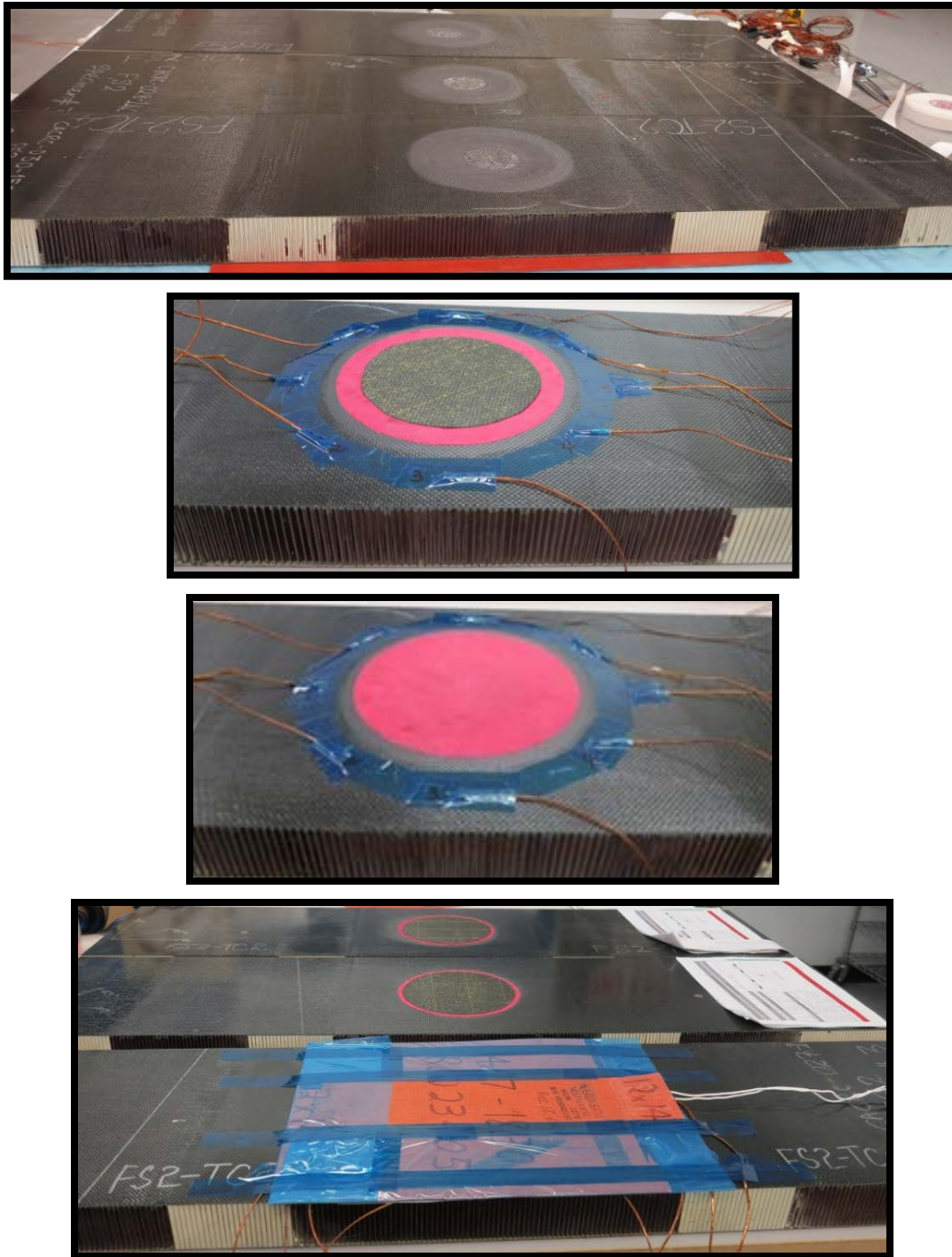


Figure 30. CACRC prepreg repairs conducted at depot 5

Figure 31 provides an overview of OEM prepreg repairs conducted at the OEM factory using the OEM materials and a proprietary process for repair application. The figure shows scarfed panels with two different scarf overlaps: a 0.25-inch overlap and a 0.5-inch overlap, with Mylar templates showing the outline of the repair plies. The figure also shows the adhesive and repair application, heat-blanket application, and final repair bagging.

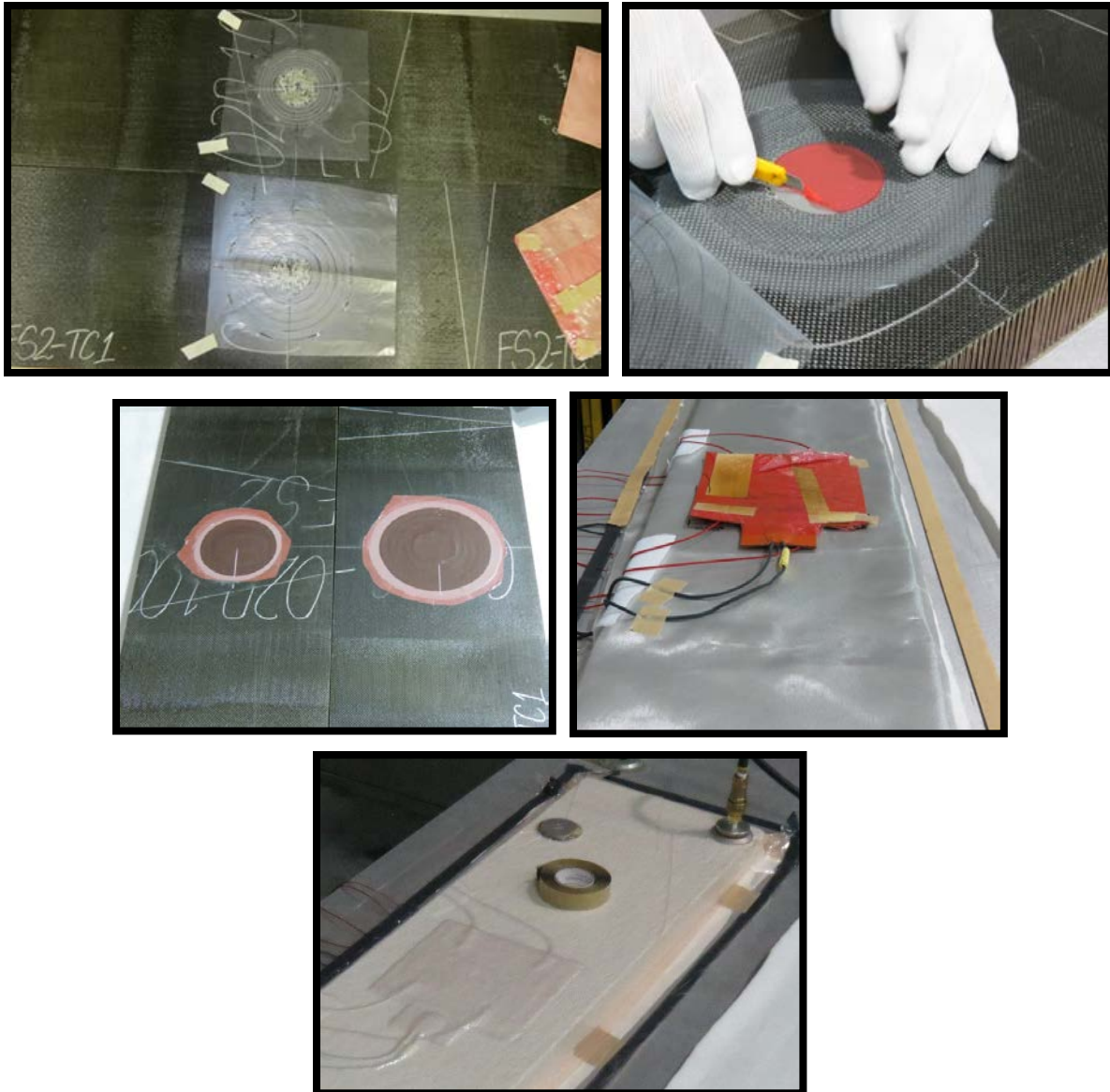


Figure 31. OEM prepreg repairs (conducted at the OEM factory)

Figure 32 provides an overview of OEM wet lay-up repairs conducted at NIAR. The figure shows a scarfed panel ready for repair, wet lay-up repair ply impregnation, film adhesive and wet lay-up repair ply application, repair bagging, heat-blanket application, and repair final curing.

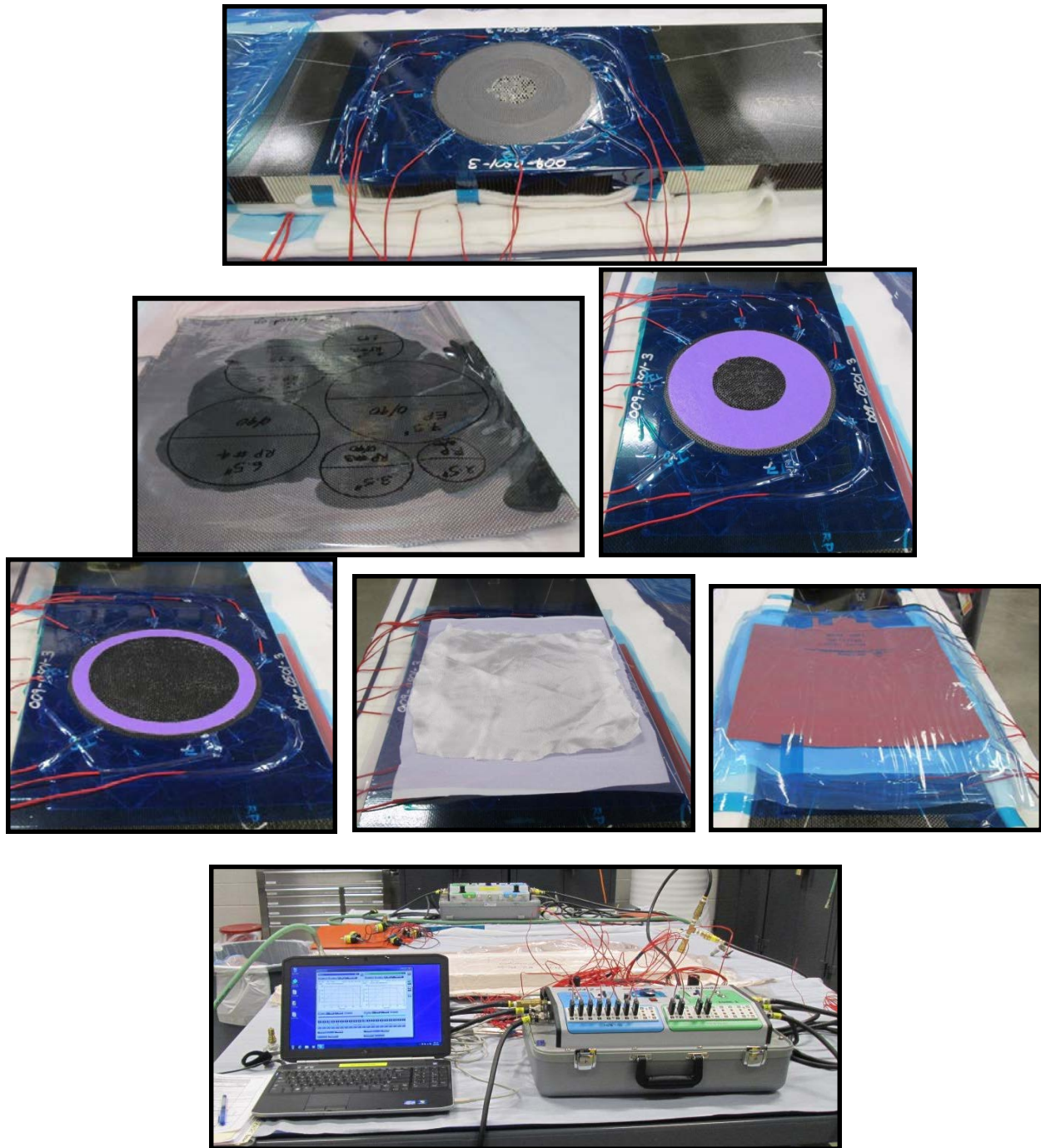


Figure 32. OEM wet lay-up repairs conducted at NIAR; repair checklist review and findings; composite repair key processing parameters

3.8 REPAIR CHECKLIST REVIEW AND FINDINGS – COMPOSITE REPAIR KEY PROCESSING PARAMETERS

A detailed review of the process checklists completed by depot personnel for each repair outlined critical composite repair processing parameters that could affect the strength of the repair. These processing parameters can be summarized as follows:

Environment/ Timeframe for Repair Execution

- Repair Station Environment
- Timeframe for repair performance and execution

Repair materials

- Repair Material out time and storage life
- Batches of materials used

Panel Preparation/Inspection Prior to Repair

- Surface preparation
- Quality of the repair scarf (morphology)
- Fitness of the interface for bonding (pre-bond moisture, contamination)

Repair Application

- Number of filler plies (when applicable)
- Ply alignment/ sequence
- Resin Mixing Ratios (Wet Lay-up Repairs)
- Resin Work Life (Pot Life, Wet Lay-up Repairs)

Repair Cure

- Repair Bagging Scheme and Materials
- Heat Blanket and Thermocouple Installation (Hot Bonder Calibration)
- Time lag between drying and final cure
- Repair Cure Cycle Ramp Up Rate
- Repair Cure Dwell Time
- Vacuum Level Achieved during Repair cure (sea level, high altitude)

CACRC prepreg repair checklist review and findings:

The CACRC prepreg repairs were performed at different timeframes over 15 months. The repair-station environment was not documented for some of the repairs, and the temperature exceeded 70°F. Although the prepreg material used for repair was still within its shelf life, the adhesive material was close to its shelf-life limit and maximum out time in some cases. All the repairs were

performed using the same batch of prepreg material, and two adhesive batches were used for the repairs. Some of the repairs were not performed immediately after drying and sat unattended in an uncontrolled environment for nearly a month in some cases. The following comments were received with one of the repair checklists: “concerning repair station environment information, all 3 prepreg panels were prepared at the same time up to step 10. From that point on, steps 10–14 each panel was handled individually. Because of holidays, vacation and local work demands for other products, these panels sat covered with solid release til scheduling allowed”; “Cure for specimen 3 was cancelled 15 minutes after cure because I discovered that I did not put solid release in the lay-up.” One set of prepreg repairs was bagged using the vertical bleed method, even if the instructions specified the no-bleed method for these repairs. The ramp-up rate that was used for the repairs varied between 3 and 5°F; the soak time varied between 180 and 240 minutes, and the vacuum level achieved for the different repairs varied between 22 and 27 inches Hg.

CACRC wet lay-up repair checklist review and findings:

The CACRC wet lay-up repairs were performed at different timeframes over 15 months. The repair station environment was not documented for some of the repairs, and the temperature exceeded 70°F. All wet lay-up repairs were performed using two batches of resin. One of the repair participants performed five wet lay-up repairs instead of three and did not identify four of the five wet lay-up repair panels on the repair checklists. As a result, it was not possible to correlate the repair process, records, and residual strength for these four panels. Similar to the prepreg repairs, some of the wet lay-up repairs were not performed immediately after drying and sat unattended in an uncontrolled environment for nearly a month in some cases.

The ramp-up rate that was used for the repairs varied between 3 and 5°F. The soak time varied between 120 and 180 minutes, and the vacuum level achieved for the different repairs varied between 23 and 27 inches Hg. For one of the repairs, the prepreg cure cycle was used instead of the wet lay-up cure cycle leading to repair overcure. For another repair, a 2-step cure was used with a 1-hour dwell at 180°F and a 2-hour dwell at 200°F, a clear deviation from the repair instructions.

4. MECHANICAL TESTING

4.1 MOISTURE CONDITIONING

All “wet” conditioned samples were exposed to elevated temperature and humidity conditions: $85 \pm 5\%$ relative humidity and $145 \pm 5^\circ\text{F}$ until equilibrium moisture weight gain of traveler or witness coupons was achieved. ASTM D5229 procedure C [33] was used as a guideline for environmental conditioning and moisture absorption.

Effective moisture equilibrium was achieved when the average moisture content of the traveler specimen changed by less than 0.02% for two consecutive readings within a span of 7 ± 0.5 days and is expressed by:

$$\frac{W_i - W_{i-1}}{W_b} < 0.02\% \quad (1)$$

W_i = weight at current time
 W_{i-1} = weight at previous time
 W_b = baseline weight prior to conditioning

A representative moisture conditioning chart is shown in figure 33.

All the elements used for this research work were environmentally conditioned after repair to simulate an aged repair subjected to an in-service environment. Facesheet and sandwich travelers were used to monitor moisture uptake in the repair elements. The average facesheet moisture content for all repair elements was 1.01%.

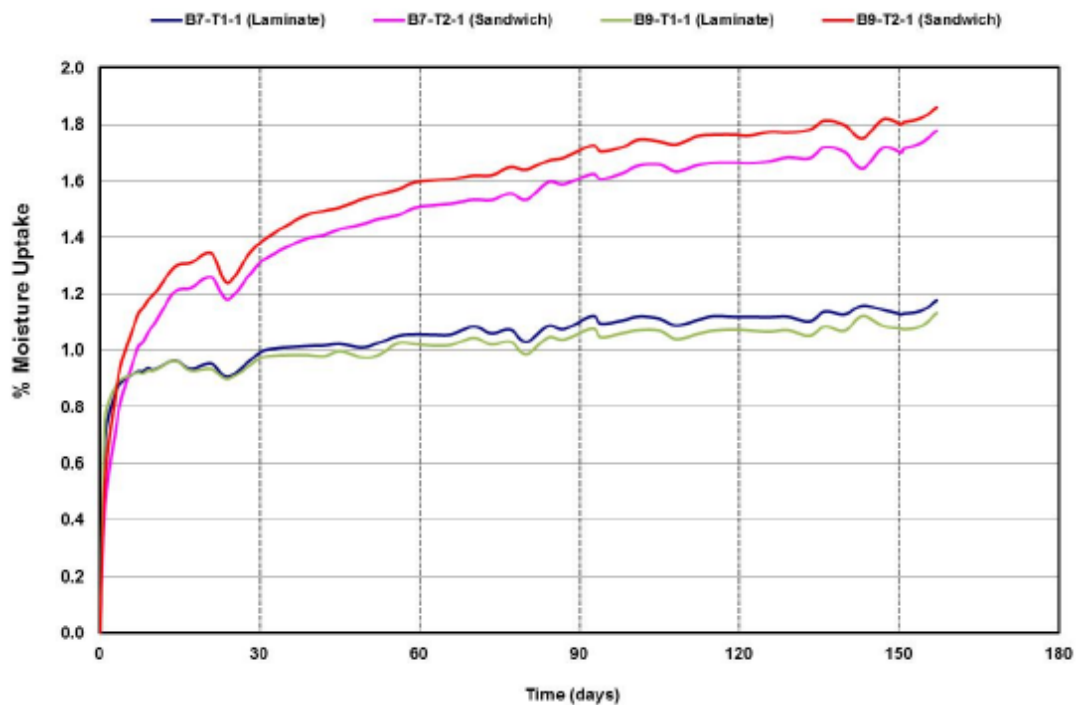


Figure 33. Representative moisture conditioning chart for a CACRC repair element

4.2 SPECIMEN INSTRUMENTATION

Strain gauges were installed in the large beam elements used for the CACRC round robin investigation. Strain gauges were applied in all repair elements in seven locations, as shown in figure 34. Strain gauges 1, 3, 5, and 7 were installed in the compression surface (repair surface), and strain gauges 2, 4, and 6 were installed in the tension surface. A deflection transducer was used at the center of the beam to monitor beam deflection:

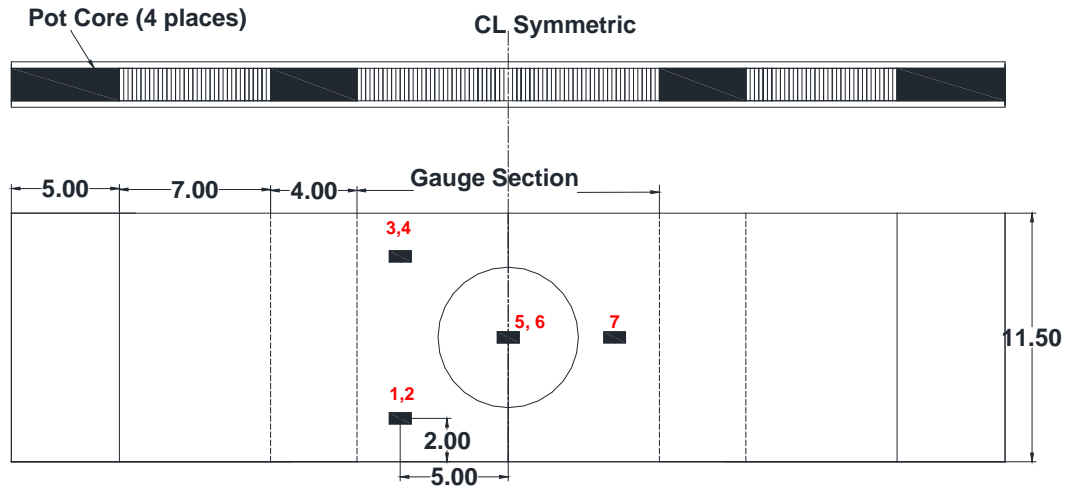


Figure 34. CACRC repair-element strain-gauge layout

4.3 LONG BEAM FLEXURE STATIC AND FATIGUE TEST PROCEDURE

With the exception of three baseline undamaged specimens tested at RTA, all remaining specimens were tested at ETW at 180°F for ultimate strength and residual strength after fatigue. For the cyclic specimens, the fatigue strain was derived from the static testing, and the sandwich elements were cycled for 165,000 cycles followed by residual strength evaluation.

A custom-made, four-point bending fixture, as shown in figures 35 and 36, was used for mechanical testing. The fixture has two main components: one fastened to the floor and another fastened to the load cell. Both components have two steel bearings attached to them to simulate a four-point bending condition.

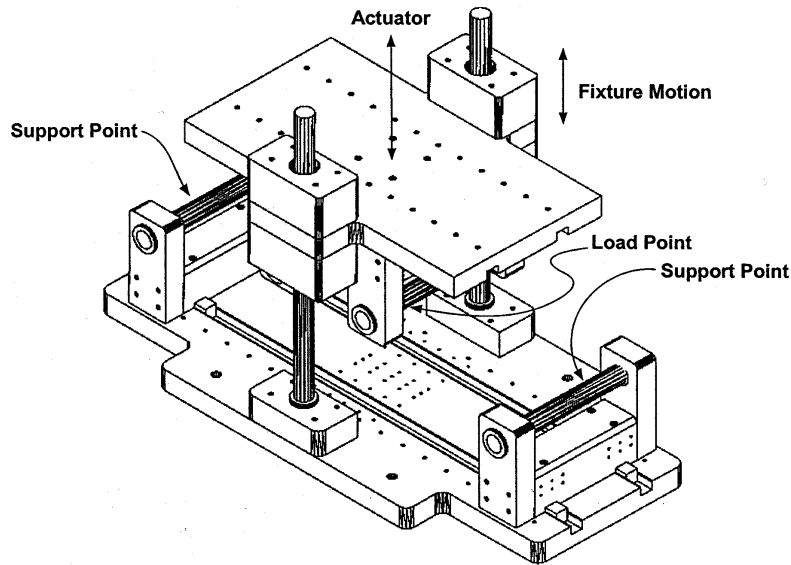


Figure 35. Isometric view of four-point bending test fixture

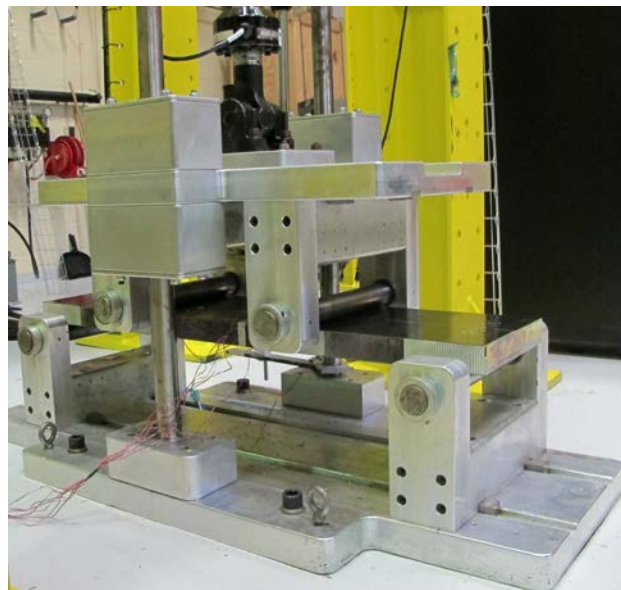


Figure 36. Long beam flexural test setup at room temperature

Load was applied using two cylindrical upper steel bearings positioned 18 inches apart. These bearings were in contact with the upper facesheet of the coupon such that the load applied was uniformly distributed along the areas of contact of the bearings with the specimens. The lower steel bearings acted as simple supports for the large beam elements. The four-point bending fixture was set up with an 18-inch loading span and a 44-inch support span, as shown in figure 35, and used a 10-kip servohydraulic actuator for loading. The test machine was calibrated periodically according to the ASTM E4 [34] standard to ensure the accuracy of load and displacement readings.

A servo valve was used to control the amount of load applied by the actuator, which in turn was controlled using the MTS Flextest II system. Data acquisition was performed using the Basic

TestWare software. The data acquired corresponds to actuator load, displacement, deflectometer, and strain-gauge readings. Mechanical tests were conducted when all strain gauge readings were within 10%. All static tests were conducted, following the guidelines of ASTM D7249-06 [35], under displacement control at a rate of 0.2 in/min–0.25 in/min to reach the maximum load between 3–6 minutes. A deflectometer was used to monitor the bending deformation at the centerline of the coupons.

A clamshell chamber was designed, built, and installed onto the test fixture, as shown in figure 37. The chamber was used to heat up the gauge section of the repaired elements. An external Applied Test Systems heating furnace linked to a temperature controller was connected to the clamshell environmental chamber and used for heating the chamber. Copper tubing was used to transfer hot air blowing from the furnace to the clamshell chamber. The heating furnace was set up in such a way that it maintained the temperature in the clamshell environmental chamber at 180°F with a tolerance of $\pm 5^\circ\text{F}$. A temperature survey using 12 thermocouples was conducted on one of the repaired elements for 8 hours to ensure uniform temperature distribution within the gauge section, as shown in figures 38 and 39. Thermocouples 1–7 were placed in the gauge section of the repaired element on the top facesheet, and thermocouples 8–12 were placed in the gauge section on the bottom facesheet.

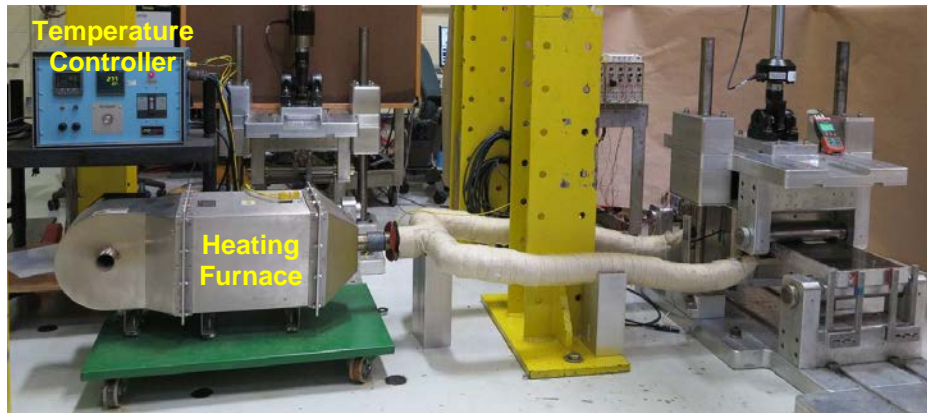


Figure 37. Long beam flexure elevated temperature test setup

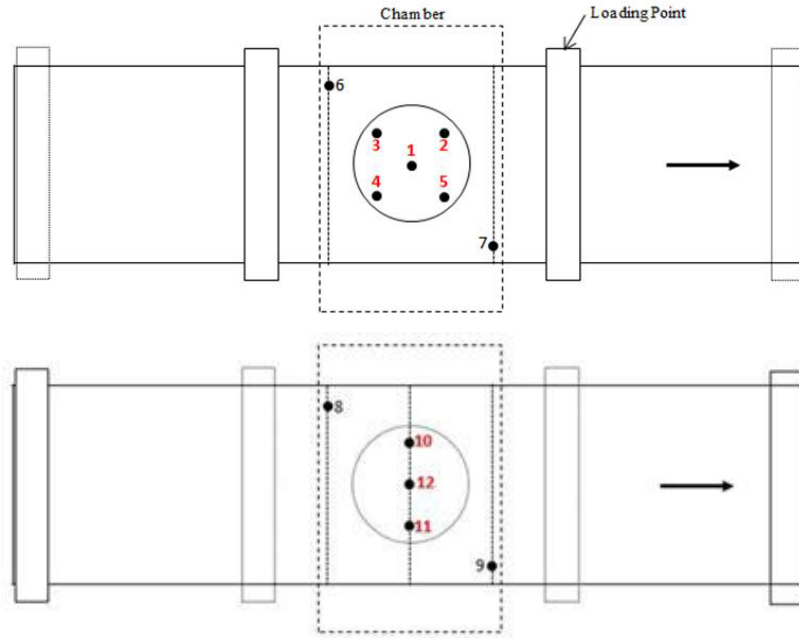


Figure 38. Thermocouple placement on gauge section of repaired elements (top and bottom facesheets)

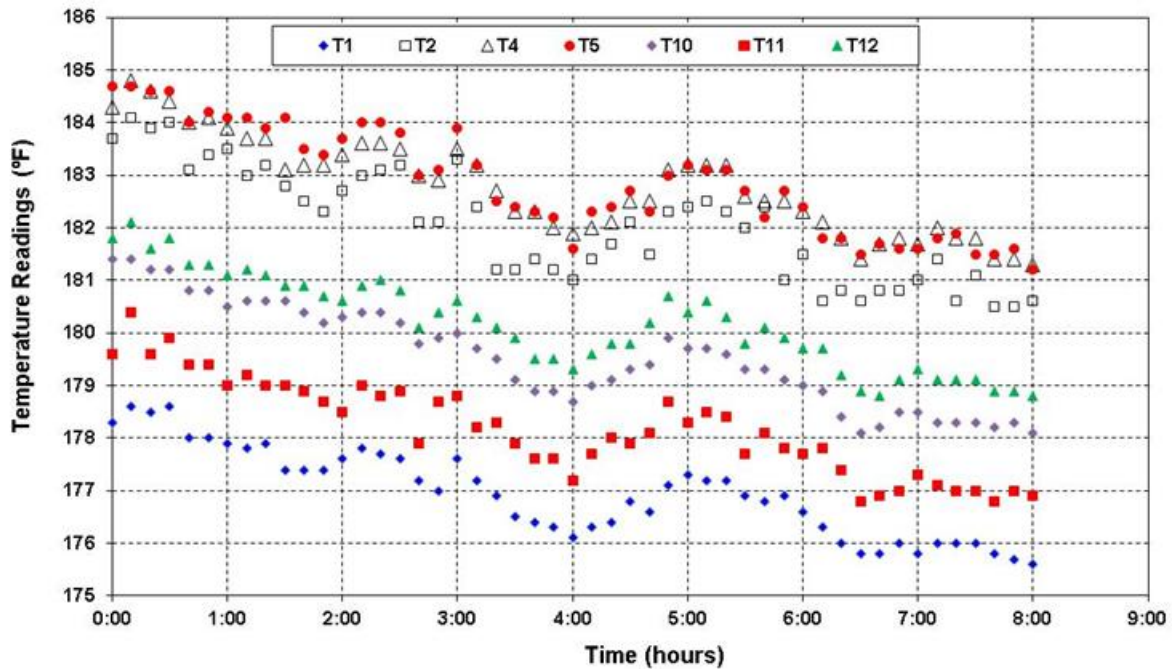


Figure 39. Temperature readings on gauge section of repaired elements

During the tests, specimen temperature was monitored using two thermocouples placed at the center of the specimen on each facesheet. Another thermocouple was placed inside the environmental chamber to monitor the air temperature of the chamber. Once the specimen was loaded onto the test fixture and the deflectometer placed at the center of the element, the position

of the environmental chamber was verified to ensure that the entire gauge section of the specimen lay within the chamber. A compressive pre-load of 10lb was applied to hold the specimen in place. The gauge section of the specimen was soaked for approximately 3–5 minutes before the test was started. The actuator and deflectometer readings were zeroed, and a test rate of 0.25 in/min was used to produce failure within 3–6 minutes.

4.4 TEST RESULTS

4.4.1 Prepreg Repair Test Results (CACRC-R1 and OEM-R1 materials)

In this section, a summary of the test results obtained from elements repaired using CACRC-R1 and OEM-R1 prepreg materials is presented. OEM-R1 repairs were performed with T300/934 PW material and FM377 adhesive (cured at 350°F) by OEM-experienced mechanics at the factory. CACRC-R1 repairs were conducted using Hexcel M20/G904 prepreg and EA9695 NW adhesive (cured at 250°F) at five operator depots and at NIAR. With the exception of the three pristine specimens tested at RTA to establish the base structure/configuration undamaged structural strength, all static and fatigue elements were tested at ETW condition at 180°F after moisture conditioning at 145°F and 85% RH. The strength results presented in this section are repair individual compression strength values tested at ETW condition at 180°F.

Round robin strength results for all elements repaired using M20 PW and EA9695 adhesive tested with the repair in compression at 180°F wet are summarized in figure 40. Individual facesheet normalized strength values for all the repair elements tested with the repair in compression are plotted in the figure. Thirty-three data points (instead of 39) are plotted. Five repairs from two depots were not completed and one element was damaged during testing. The repair data are normalized using a 0.0083-inch cured ply thickness. The repair elements tested at 180°F yielded an average ETW strength of 30.5 ksi (Min=22.1 ksi, Max=38.0 ksi). The baseline/undamaged elements tested at 180°F yielded an average ETW strength of 35.4 ksi (Min=32.9 ksi, Max=38.2 ksi). The repair strength values are compared to unrepaired open-hole scarf elements' average strength of 13.7 ksi (simulating a failed patch/repair condition). These values are also compared to the repair laminate open-hole and unnotched compression ETW B-basis values of 24 ksi and 30.1 ksi, respectively.

Sixty-one percent of all repair elements restored yielded strength values greater or equal to the ETW B-basis unnotched compression of the repaired laminate. Eighty-two percent of all repair elements yielded strength values higher than the ETW B-basis open-hole compression strength of the repaired laminate. Post-test analysis was conducted on all understrength repairs to identify root causes for the lower residual strength values. Round robin strength results for elements repaired with CACRC materials using M20 PW and EA9695 adhesive and elements repaired with OEM prepreg materials tested with the repair in compression at 180°F are summarized in figure 40. OEM-0.25-1, 2, 3 (blue columns in chart) were repaired at the OEM factory using the OEM-R1 prepreg material and a 0.25-inch scarf overlap. These repairs yielded the highest residual ETW average strength (37.7 ksi). OEM-0.5-1, 2, and 3 (yellow columns in chart) were repaired at the OEM factory using the OEM-R1 prepreg material and a 0.5-inch scarf overlap. These repairs yielded a residual ETW average strength of 33.7 ksi, comparable to that of the elements repaired with the CACRC prepreg material (columns in grey).

It should be noted that all CACRC prepreg repairs, including the six understrength repairs identified as elements 9, 10, 11, 16, 17, and 18 in figure 40 yielded facesheet compression failures either through the repairs or in the parent, all within the gauge section. None of the CACRC prepreg repairs yielded adhesion failures. All understrength repairs failed in the repair gauge section in the facesheet through the repair.

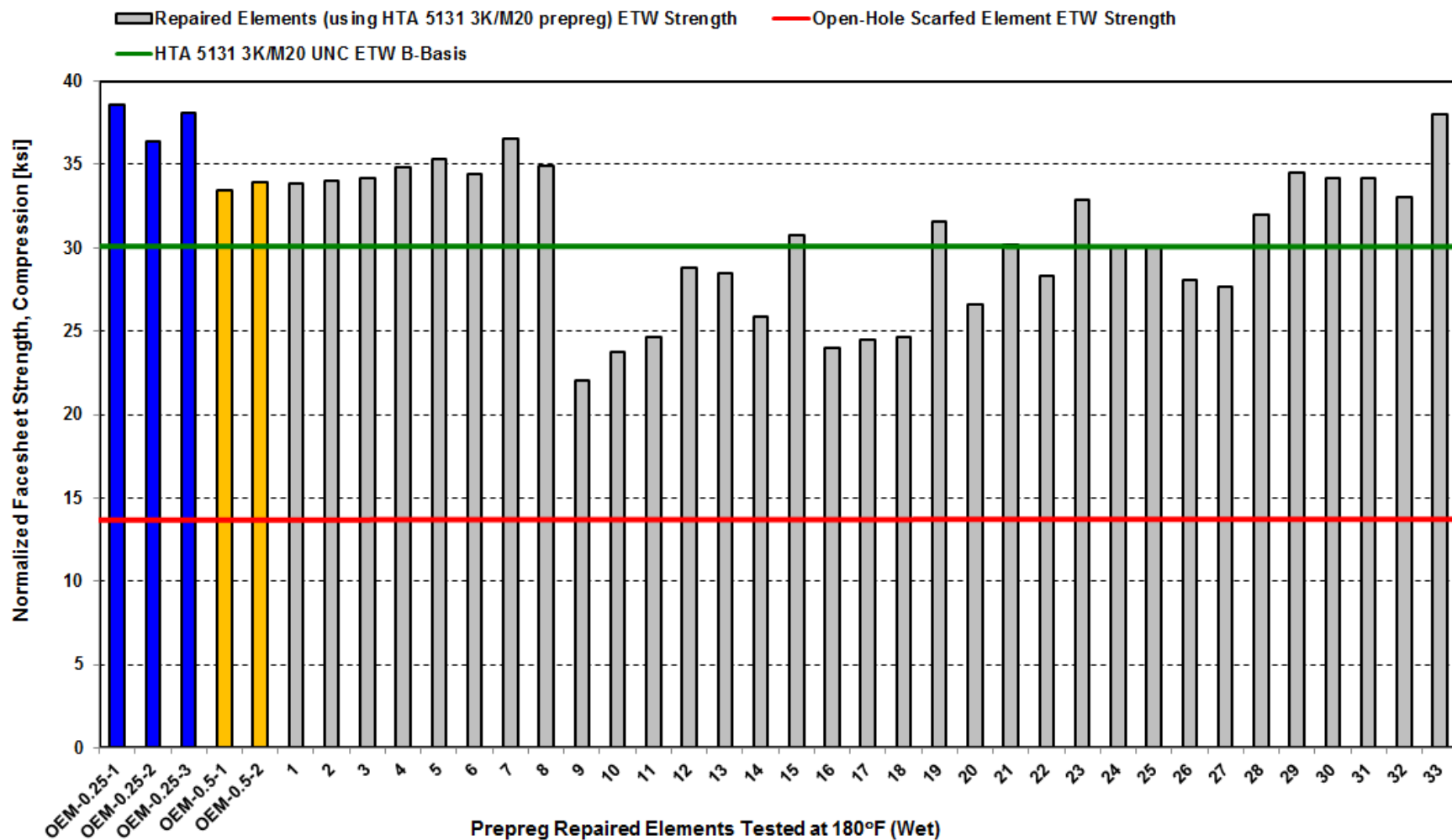


Figure 40. Round robin compression test results for all prepeg repairs tested at 180°F wet

4.4.2 Prepreg Repair Failure Modes

Representative failure modes of undamaged, open-hole scarfed, and repaired elements using CACRC and OEM prepreg materials are summarized in figures 41–45. All baseline/undamaged elements yielded facesheet compression failures in the gage section, as shown in figure 41. All open-hole scarfed elements yielded compression failures in the gage section through the open-hole, as shown in figure 42. Representative failure modes of CACRC prepreg repairs using M20PW/ EA9695 are shown in figures 43 and 44. All elements repaired with the CACRC prepreg yielded laminate compression failures in the gage section (48% failed outside the repair, 52% failed within the repair), as shown in the figures. All elements repaired with the OEM prepreg yielded laminate compression failures in the gage section outside the repair, as shown in figure 45.

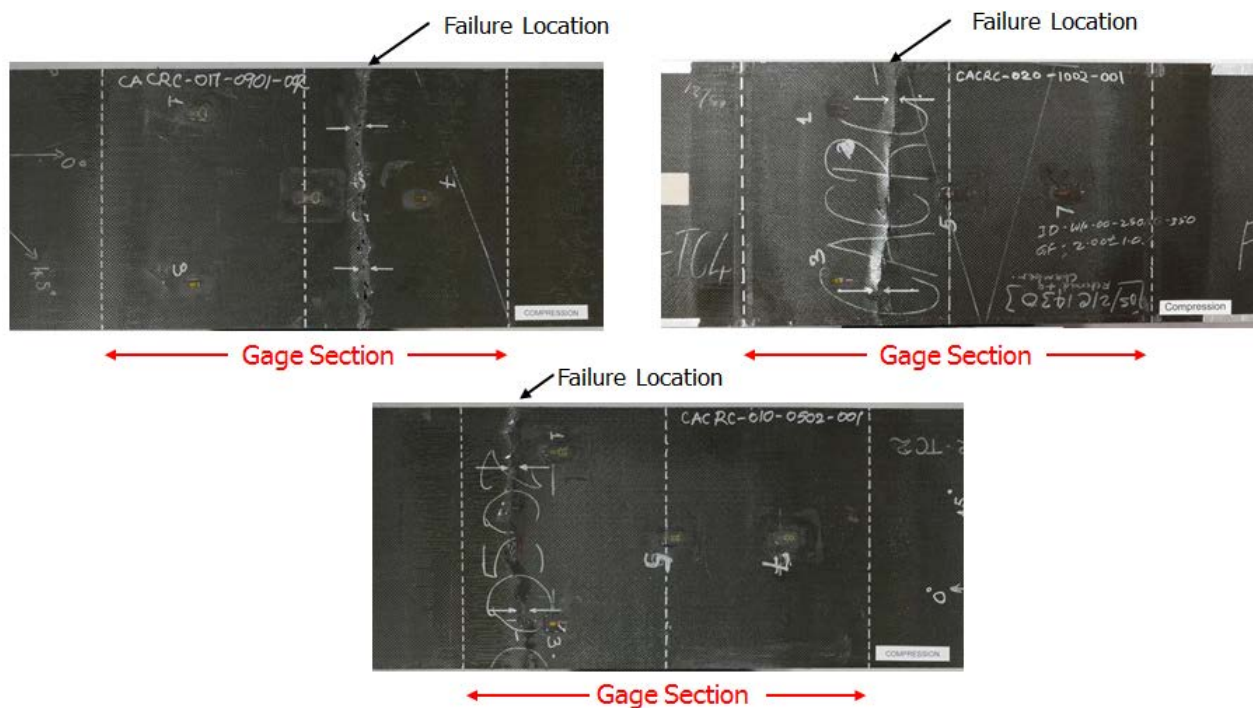


Figure 41. Representative failure modes of baseline/undamaged elements tested at 180°F

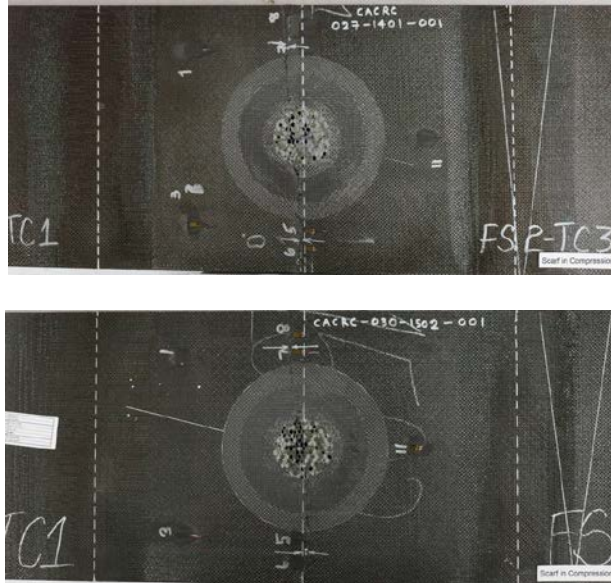


Figure 42. Representative failure modes of open-hole scarfed elements (unrepaired) tested at 180°F (this configuration simulates a patch-off/completely failed repair condition)

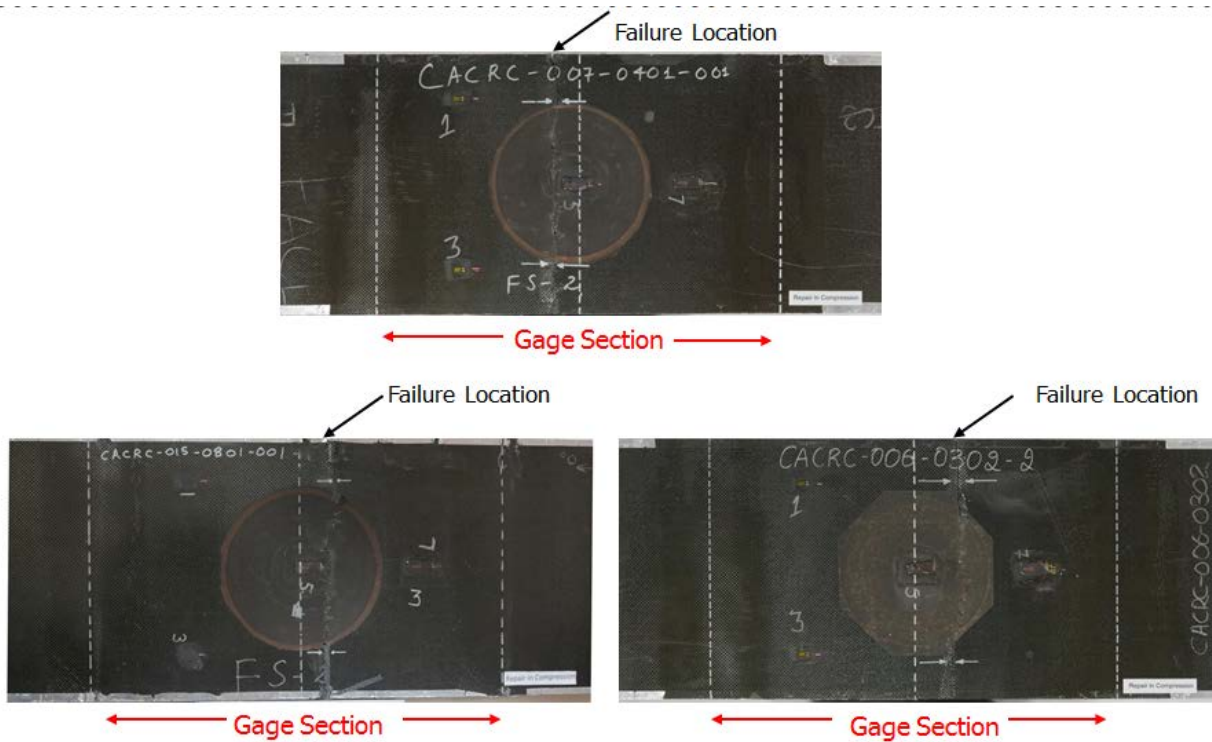


Figure 43. Representative failure modes of CACRC prepreg repairs using M20PW/EA9695 (facesheet compression failure through the repair)

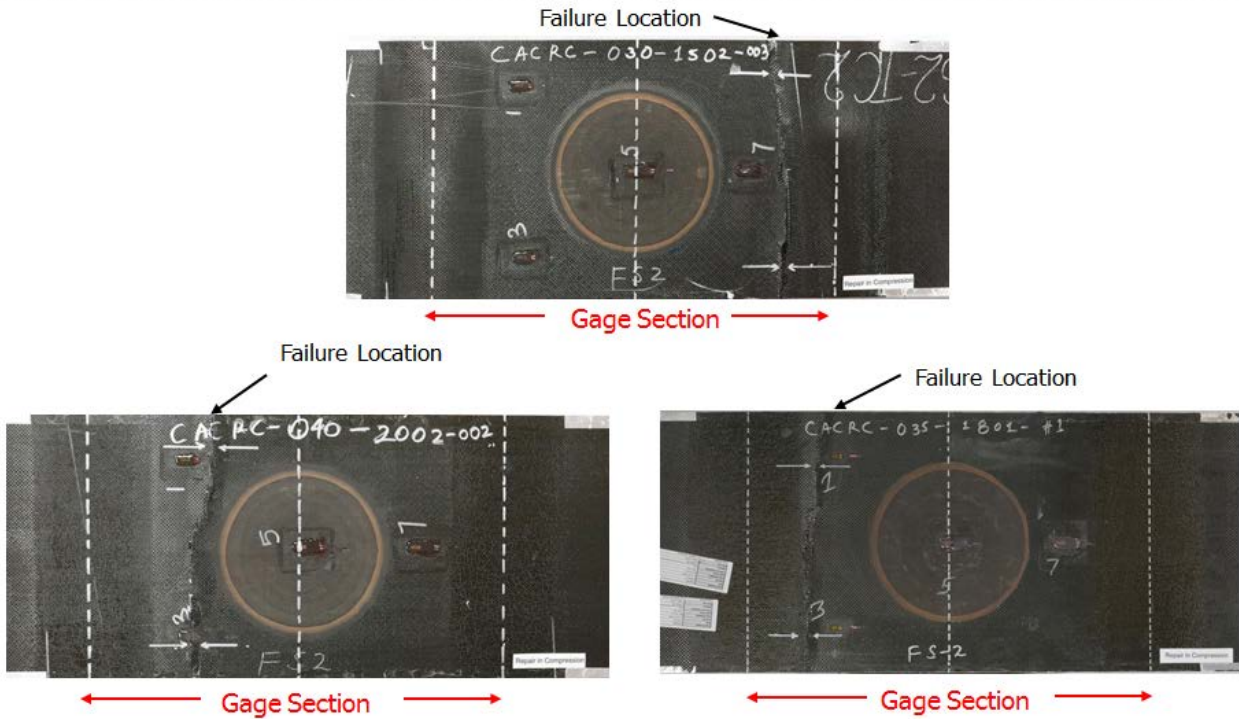


Figure 44. Representative failure modes of CACRC prepreg repairs using M20PW/EA9695 (facesheet compression failure outside the repair, through the parent)

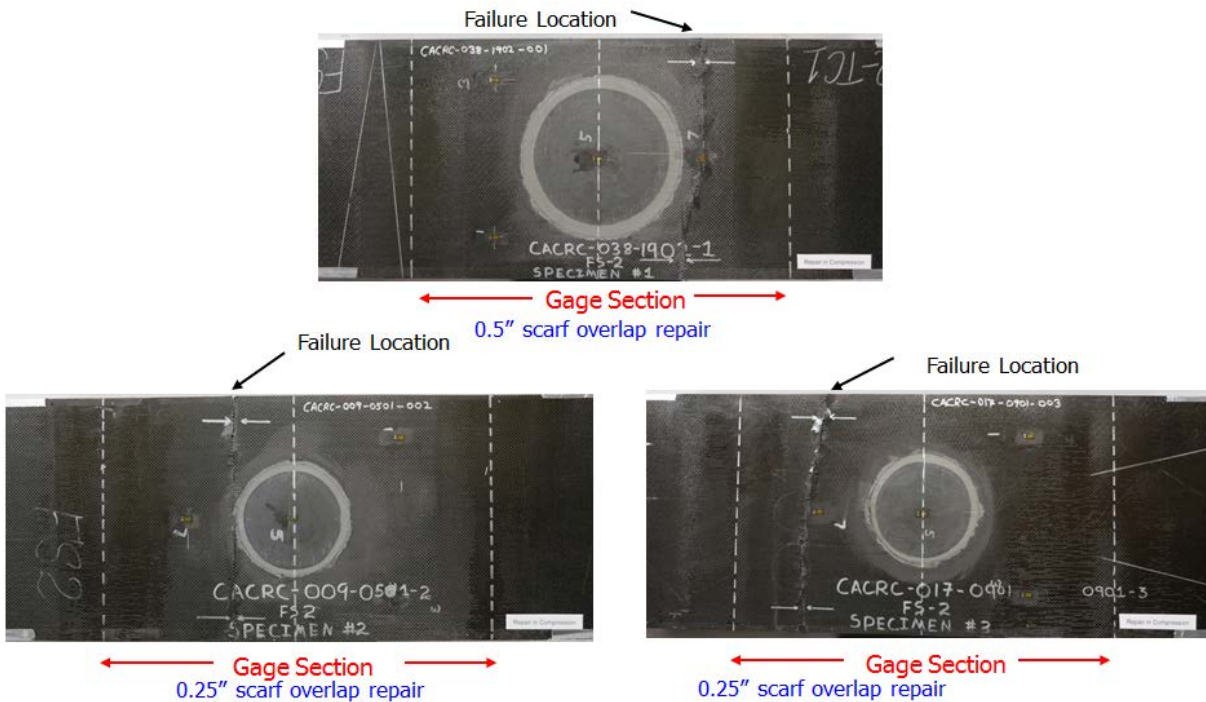


Figure 45. Representative failure modes of OEM-R1 prepreg repairs using T300/934 PW and FM377 adhesive (facesheet compression failure outside the repair, through the parent)

4.4.3 Prepreg Repair Variability by Operator

Test results obtained from elements repaired using CACRC-R1 prepreg materials by different mechanics are summarized in figure 46. Mechanics 3, 5, 7, and 9 had minimal levels of experience, and all the other technicians were experienced. CACRC-R1 repairs were conducted using Hexcel M20/G904 prepreg and EA9695 NW adhesive (cured at 250°F) at five operator depots and at NIAR. The strength results summarized in figure 46 are repair average compression strength values from a minimum of three elements tested at ETW condition at 180°F. All mechanics performed a minimum of three prepreg repairs with the exception of mechanic 3 who performed only one repair. The repair strength values were compared to unrepaired open-hole scarf elements with an average strength of 13.7 ksi (simulating a failed patch/repair condition). These values are also compared to the repair laminate open-hole unnotched compression ETW B-basis values of 24 ksi and 30.1 ksi, respectively.

It should be noted that all six understrength repairs identified as elements 9, 10, 11, 16, 17, and 18 in figure 40 were performed by operators 2 (experienced) and 5 (minimal level of experience), respectively, as shown in figure 46. This demonstrates that repairmen experience alone is not a predictor of repair performance.

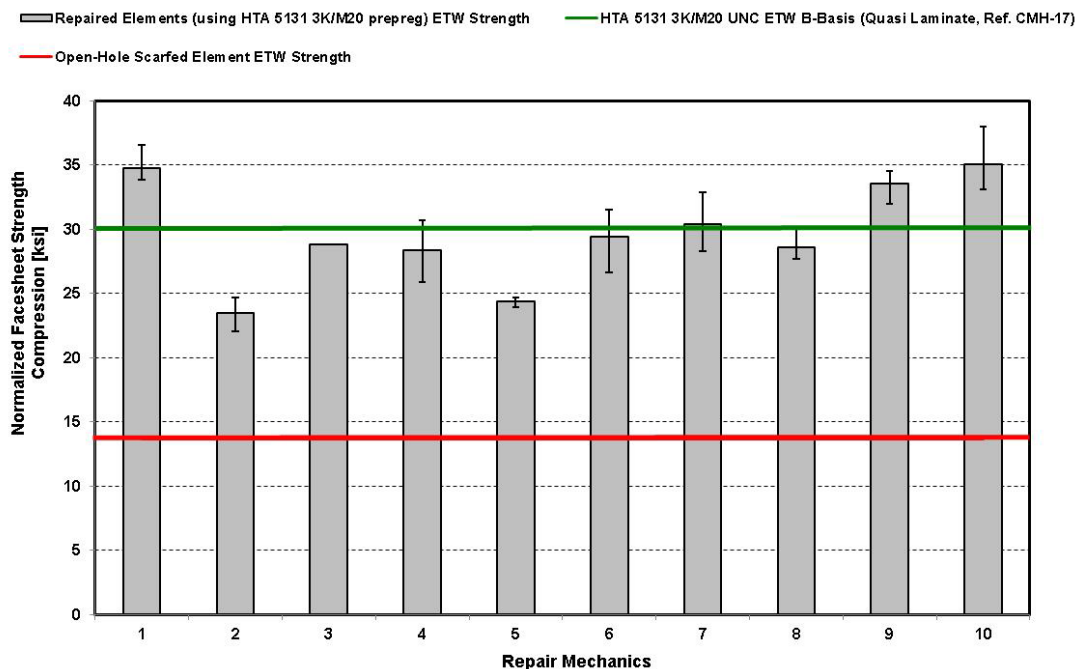


Figure 46. Round robin compression test results for CACRC prepreg repairs (M20 PW/ EA9695 adhesive tested at 180°F Wet) performed by different mechanics

4.4.4 NDI After Repair

NDI using TTU was conducted on all panels before and after repair. A 1 MHz transducer was used for all inspections. The following is a summary of the NDI results and failure modes for the CACRC prepreg repairs with the highest and lowest residual strength. C-scans and post-test

pictures of the repairs with the lowest residual strengths are shown in figures 47–52, with scans of panels 16 and 17 showing a clear indication of porosity in the repair (figures 50 and 51). C-scans and post-test pictures of three of the repairs with the highest residual strengths are shown in figures 53–55.

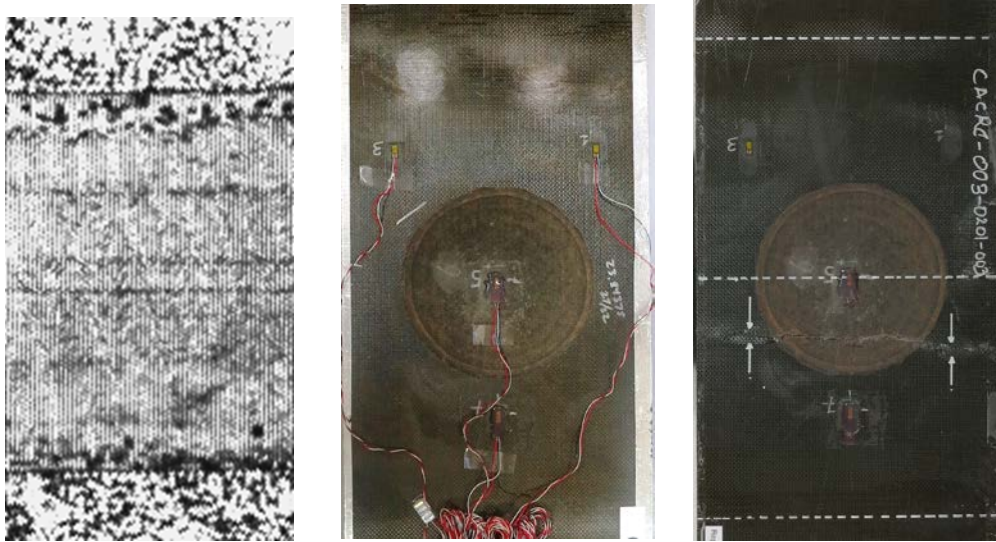


Figure 47. CACRC-003-0201-003-P-RC-ETW (element 9), TTU scan, pre- and post-test picture (understrength repair)



Figure 48. CACRC-021-1101-001-P-RC-ETW (element 10), TTU scan, pre- and post-test picture (understrength repair)

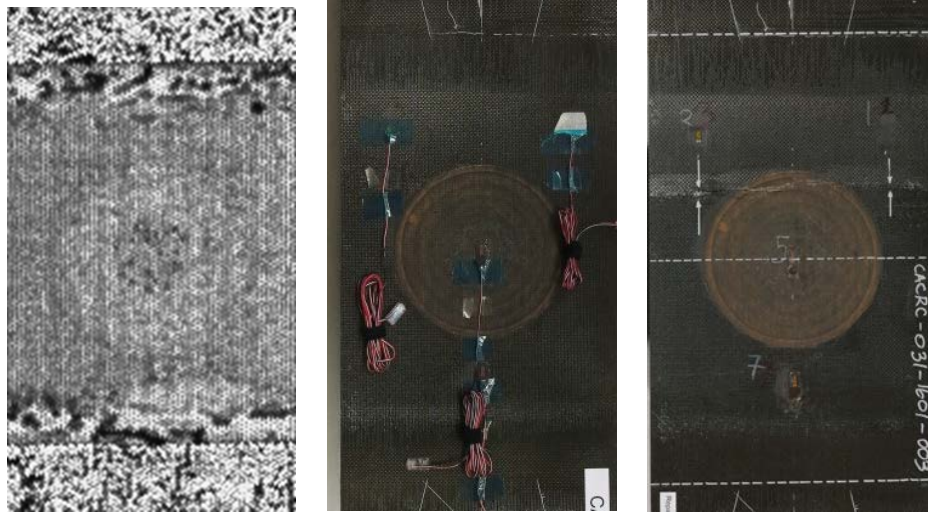


Figure 49. CACRC-031-1601-003-P-RC-ETW (element 11), TTU scan, pre- and post-test picture (understrength repair)

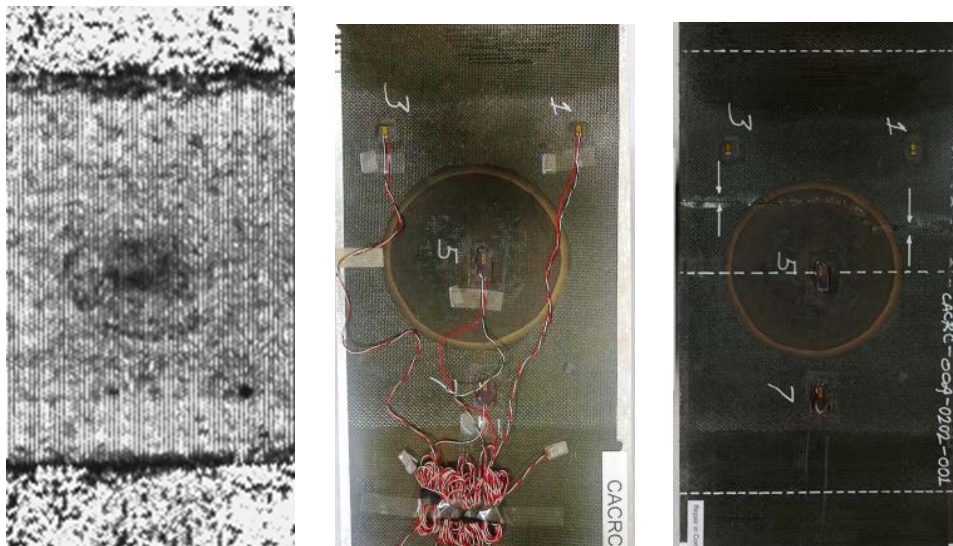


Figure 50. CACRC-004-0202-001-P-RC-ETW (element 16), TTU scan, pre- and post-test picture (understrength repair)

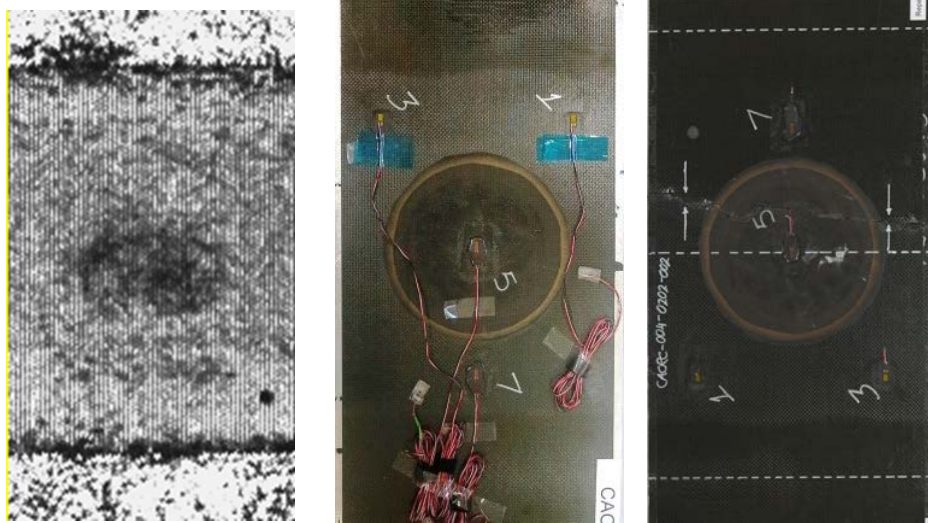


Figure 51. CACRC-004-0202-002-P-RC-ETW (Panel 17), TTU scan, pre- and post-test picture (understrength repair)

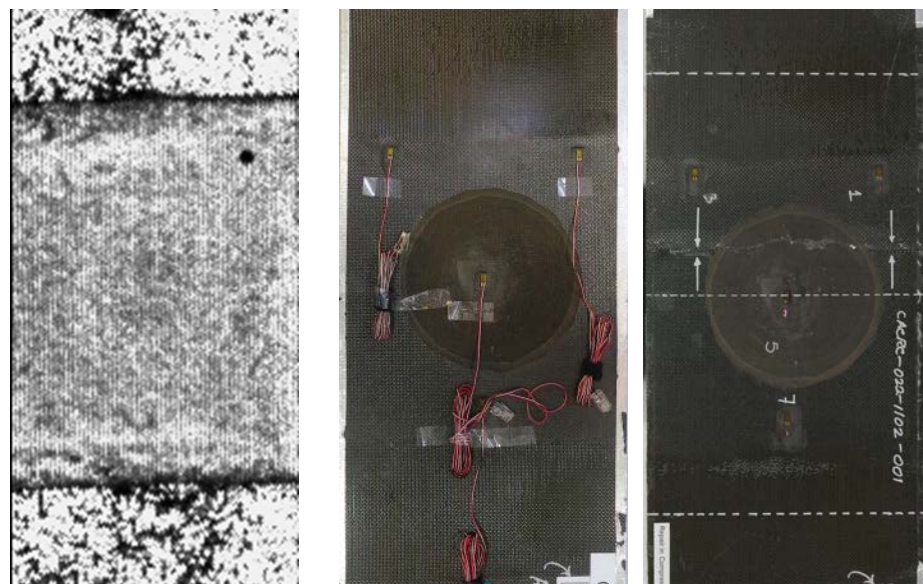


Figure 52. CACRC-022-1102-001-P-RC-ETW (Panel 18), TTU scan, pre- and post-test picture (understrength repair)

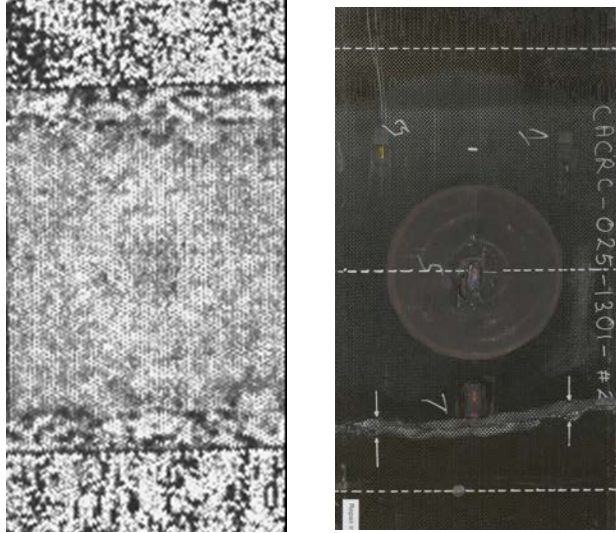


Figure 53. CACRC-025-1301-002-P-RC-ETW (element 5), TTU scan and post-test picture

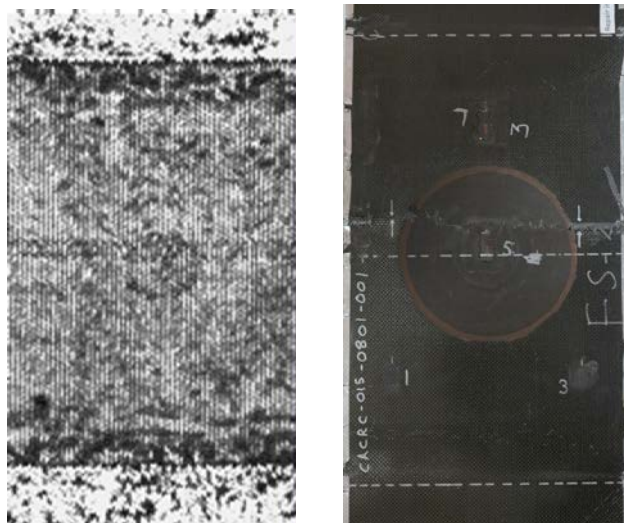


Figure 54. CACRC-015-0801-001-P-RC-ETWF (element 7), TTU scan, and post-test picture

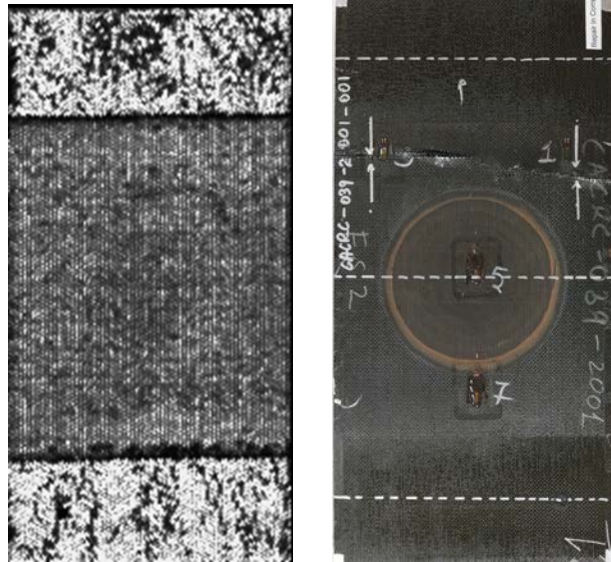


Figure 55. CACRC-039-2001-001-P-RC-ETW (element 33), TTU scan and post-test picture

4.4.5 Prepreg Repair Post-Test Analysis

Post-test physical, thermal, and optical analysis of CACRC prepreg repairs was conducted on the understrength repairs and repairs that demonstrated good performance and residual strength. The goal of the analysis was to determine the physical and thermal properties of the parent and repair materials and identify possible anomalies that might have contributed to the low residual-strength repairs. (A post-test analysis map is shown in figure 56.) Dynamic mechanical analysis (DMA), Differential scanning calorimeter (DSC), and physical test samples were extracted from the center of the repair but also from parent material adjacent to the repair, as shown in the figure. Section cuts along the width of the repair element were used to inspect the quality of the parent and repair laminate, as shown in figure 56.

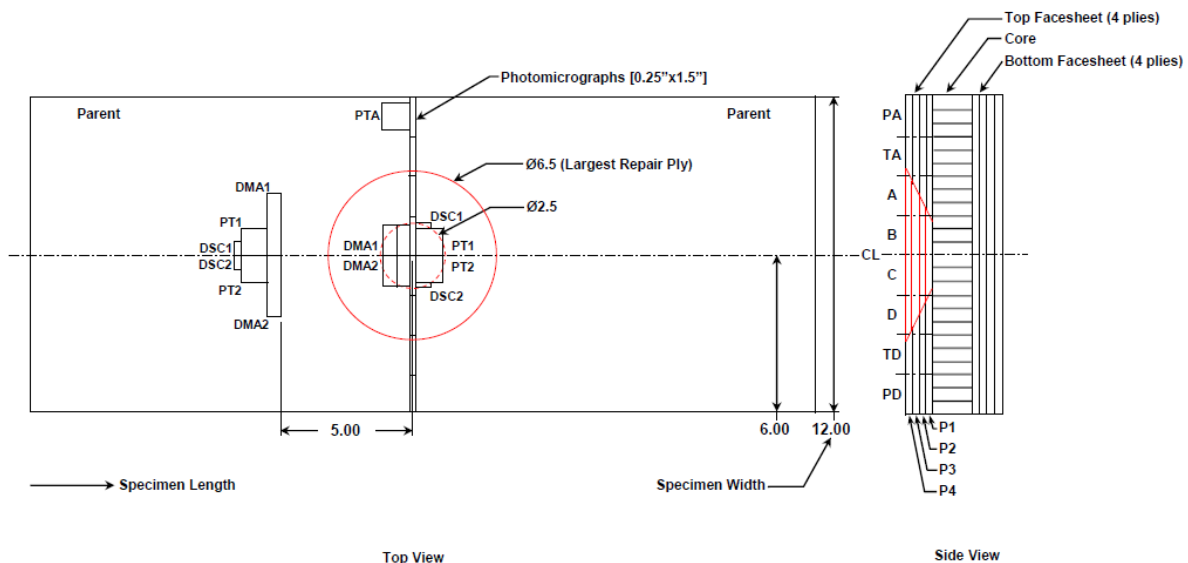


Figure 56. CACRC post-test analysis map

After reviewing the repair checklists for elements 9, 10, and 11 of figure 40 performed by operator 2, the following process deviations may have contributed to the lower residual strengths of these repairs:

- The vertical bleed method was used to bag the repairs instead of the no-bleed method, as specified in the repair instructions.
- There was a 1-month time lapse between the time the scarfed specimens were dried and the time they were repaired: “panels sat covered with solid release till scheduling allowed for repair up to 1 month.” “Concerning repair station environment information, all three prepreg panels were prepared at the same time up to step 10. From that point on, steps 10-14 each panel was handled individually. Because of holidays, vacation and local work demands for other products, these panels sat covered with solid release til scheduling allowed.”
- Cure cycle was interrupted, then restarted: “cure for spec 3 was cancelled 15 min after cure because I discovered that I did not put solid release in the lay-up.”

Physical test results also showed a very porous repair for element 10. After reviewing the repair checklists for elements 16, 17, and 18 of figure 40 performed by operator 5, no obvious process deviations were found on the repair records. However, all three panels yielded very porous repairs (8.5%, 8.5%, and 5.6%) from physical tests by acid digestion and (9.6%, 11.8%, and 5.5%) respectively from optical analysis.

A cross section of CACRC-004-0202-002 (element 17, sections C and B) through the center section of the CACRC prepreg repair is shown in figures 57 and 58. Both figures show high porosity levels in the repair and confirm the void content obtained from physical test results. Similarly, a cross section of CACRC-037-1901-003 (element 29, sections C and B) through the center section and the scarfed section of the CACRC prepreg repair is shown in figures 59 and 60. Both figures show lower porosity levels in the repair and confirm the void content obtained from physical test results.

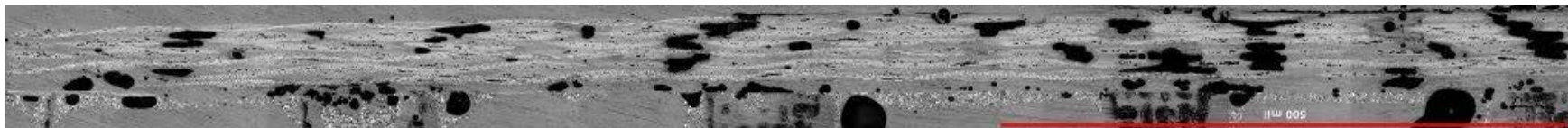


Figure 57. CACRC-004-0202-02-PM-C



Figure 58. CACRC-004-0202-02-PM-B



Figure 59. CACRC-037-1901-03-PM-C



Figure 60. CACRC-037-1901-03-PM-B

4.4.6 Wet Lay-up Repair Test Results (CACRC-R2 and OEM-R2 materials)

In this section, a summary of the test results obtained from elements repaired using CACRC-R2 and OEM-R2 wet lay-up materials is presented. OEM-R2 repairs were performed using T300 3K fabric with EA9396 C2 laminating resin and EA9696 adhesive at NIAR. CACRC-R2 repairs were conducted using G904 D1070 TCT fabric with Epocast 52A/B (200°F cure repair, wet lay-up) at NIAR and five operator depots. With the exception of the three pristine specimens tested at RTA to establish the base structure/configuration undamaged strength, all static and fatigue elements were tested at ETW condition at 180°F after moisture conditioning at 145°F and 85% RH. The strength results presented in this section are repair element individual parent facesheet compression strength values at ETW condition tested at 180°F.

Round robin strength results for all wet lay-up repair elements performed using G904 D1070 TCT fabric with Epocast 52A/B tested with the repair in compression at 180°F wet are summarized in figure 61. Individual parent facesheet normalized strength values for all the repair elements tested with the repair in compression are plotted in the figure. Thirty-five data points instead of 36 are plotted (three repairs from one depot were not completed and one operator performed five wet lay-up repairs instead of three). The wet lay-up repair elements tested at 180°F yielded an average ETW parent strength of 32.1 ksi (min=13.7 ksi, max=42.7 ksi). The baseline/undamaged elements tested at 180°F yielded an average ETW strength of 35.4 ksi (min=32.9 ksi, max=38.2 ksi). The strength values at failure are compared to unrepaired open-hole scarf elements' average strength of 13.7 ksi (simulating a failed patch/repair condition). These values are also compared to the parent laminate unnotched compression ETW B-basis estimate of 30.0 ksi.

Seventy-seven percent of all repair elements restored yielded strength values greater or equal to the ETW B-basis unnotched compression of the parent laminate. Post-test analysis was conducted on all understrength repairs to identify root causes to the lower residual strength values. Figure 61 also summarizes parent strength for repair elements using OEM wet lay-up materials tested with the repair in compression at 180°F. OEM-0.5-1, 2, 3, 4, 5, and 6 (blue columns in figure 61) were repaired at NIAR using the OEM-R2 wet lay-up material and a 0.5-inch scarf overlap. These repairs yielded higher residual ETW average parent facesheet strength (33.0 ksi) than the elements repaired with the CACRC-R2 wet lay-up material (columns in grey).

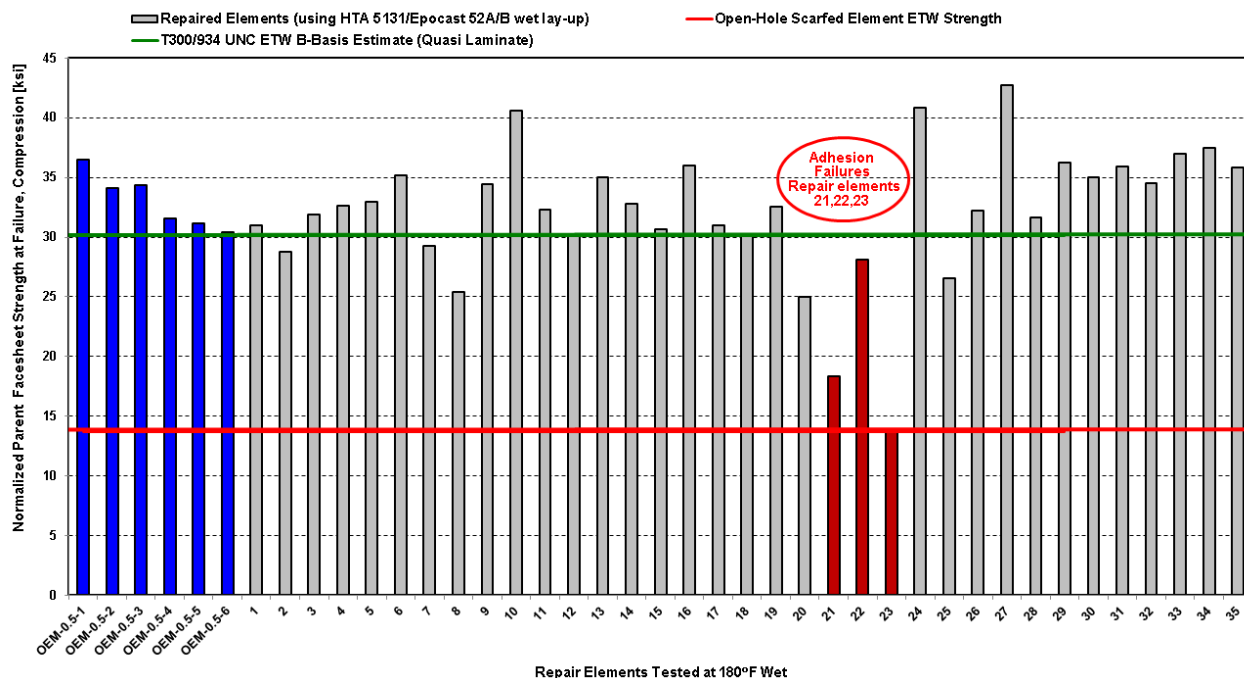


Figure 61. Round robin compression test results for all wet lay-up repairs tested at 180°F wet

It should be noted that all CACRC wet lay-up repairs yielded facesheet compression failures, either through the repairs or in the parent, all within the gauge section, with the exception of elements 21, 22, and 23, which had adhesion failures in the repair. All OEM wet lay-up repairs yielded facesheet compression failures either in the parent or the repair.

4.4.7 Wet Lay-Up Repair Failure Modes

Representative failure modes of repaired elements using CACRC and OEM wet lay-up materials are summarized in figures 62–66. All baseline/undamaged elements yielded facesheet compression failures in the gauge section, as shown in figure 41. All open-hole scarfed elements yielded compression failures in the gauge section through the open hole, as shown in figure 42. Representative failure modes of CACRC wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B are shown in figures 62–64. All elements repaired with the CACRC wet lay-up material yielded laminate compression failures in the gauge section (34% failed outside the repair, 66% failed within the repair), as shown in figures 62 and 63 with the exception of three repairs that had adhesion failures, as shown in figure 64. All elements repaired with the OEM wet lay-up material (T300 3K fabric with EA9396 C2 laminating resin and EA9696 adhesive) yielded laminate compression failures in the gauge section, either within the repair or outside the repair through the parent, as shown in figures 65 and 66. There were no adhesion failures for the repairs performed with the OEM wet lay-up material.

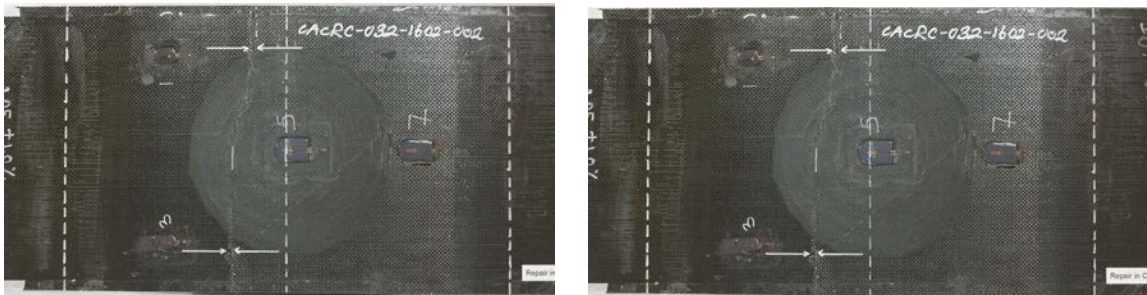


Figure 62. Representative failure modes of CACRC wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (facesheet compression failure through the repair)

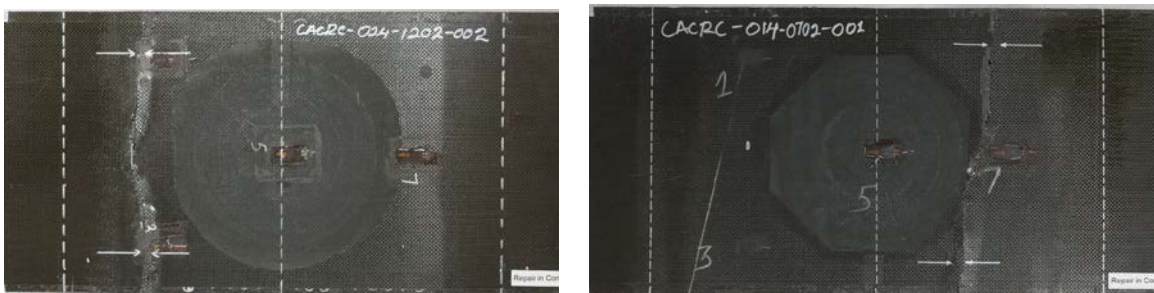


Figure 63. Representative failure modes of CACRC-R2 wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (facesheet compression failure outside the repair, through the parent)

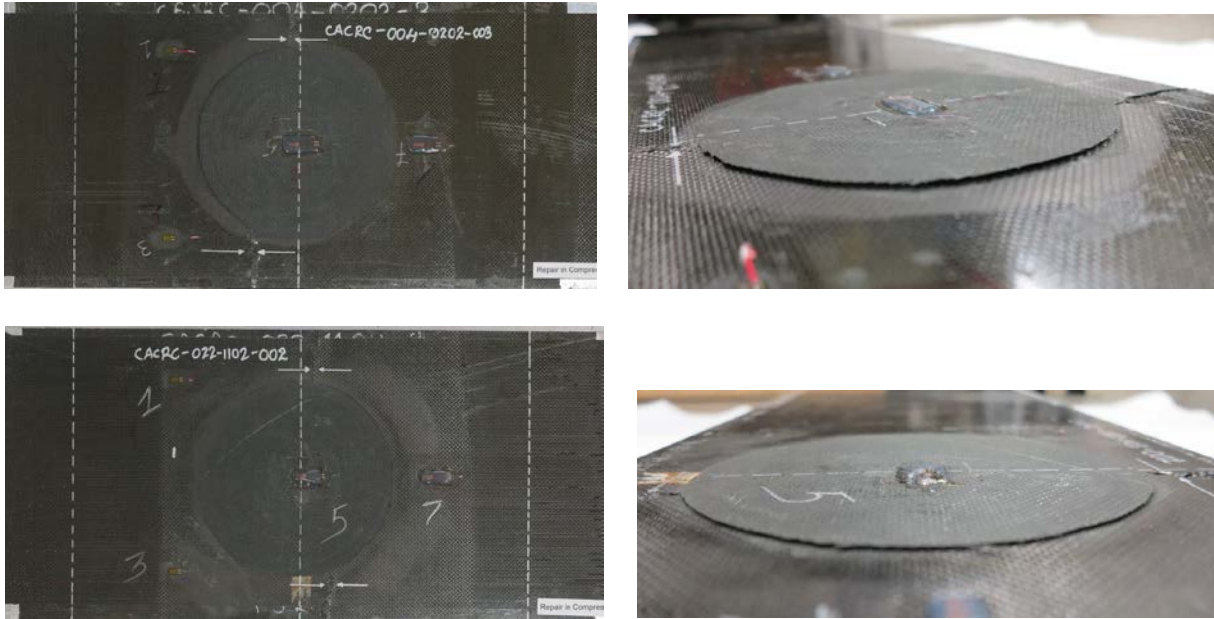


Figure 64. Representative failure modes of CACRC-R2 wet lay-up repairs using G904 D1070 TCT fabric with Epocast 52A/B (adhesion failures)

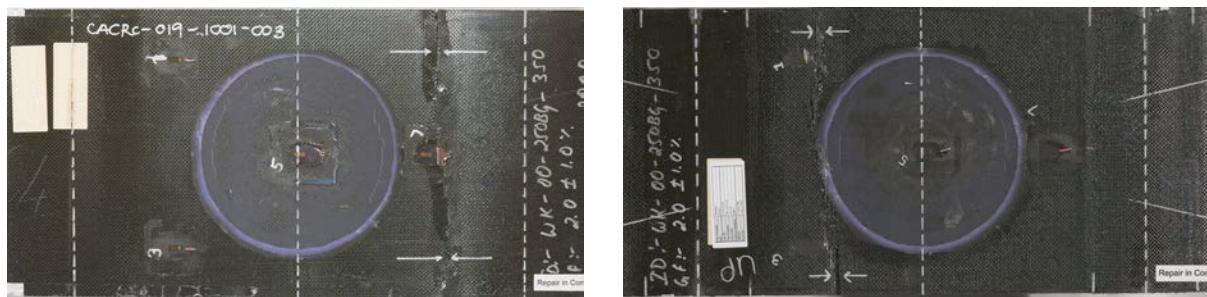


Figure 65. Representative failure modes of OEM-R2 wet lay-up repairs using T300 3K fabric, EA9396 C2 laminating resin, and EA9696 adhesive (facesheet compression failure outside the repair, through the parent)

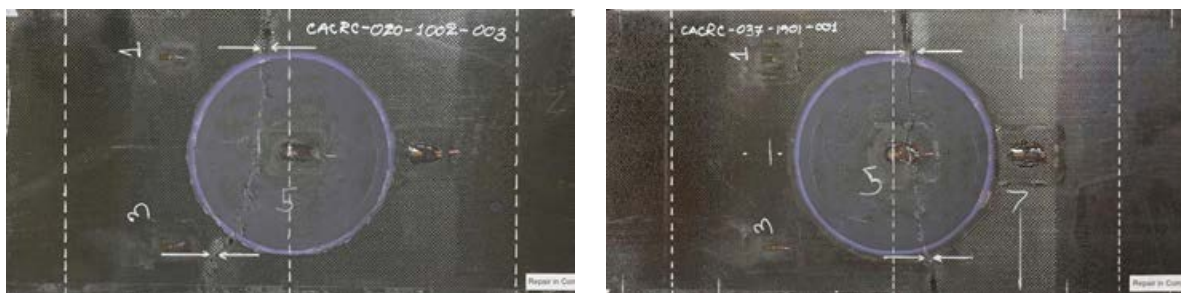


Figure 66. Representative failure modes of OEM-R2 wet lay-up repairs using T300 3K fabric, EA9396 C2 laminating resin, and EA9696 adhesive (facesheet compression failure through the repair)

4.4.8 Wet Lay-up Repair Variability by Operator

Test results obtained from elements repaired using CACRC-R2 wet lay-up materials by different mechanics are summarized in figure 67. Mechanics 3, 5, 7, and 9 had minimal levels of experience, and all other technicians were experienced. CACRC-R2 repairs were conducted using G904 D1070 TCT fabric with Epocast 52A/B at five operator depots and NIAR. The strength results summarized in figure 67 are individual parent facesheet normalized strength values at failure for all the elements tested with the repair in compression. The strength values represent an average obtained from a minimum of three elements tested at ETW condition at 180°F. All mechanics performed a minimum of three wet lay-up repairs with the exception of mechanic 3, who performed five wet lay-up repairs. The strength values are compared to unrepaired open-hole scarf elements with average strength of 13.7 ksi (simulating a failed patch/repair condition). These values are also compared to the parent laminate compression ETW B-basis estimate of 30.0 ksi.

It should be noted that all three defective repairs yielding adhesion failures identified as elements 21, 22, and 23 in figure 61 were all performed by operator 6 (experienced), as shown in figure 67. This demonstrates that repair technician experience alone is not a sufficient predictor of repair performance.

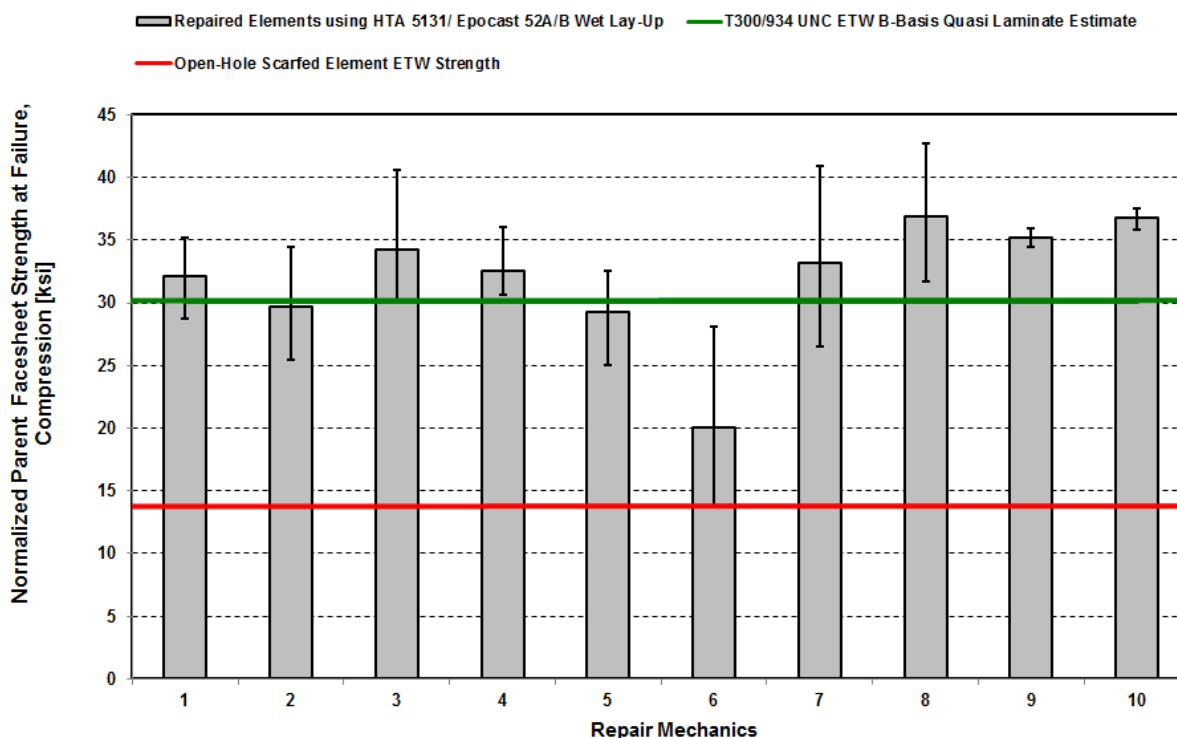


Figure 67. Round robin compression test results for CACRC wet lay-up repairs (tested at 180°F wet) performed by different mechanics

4.4.9 Wet Lay-up NDI After Repair

NDI using TTU was conducted on all panels before and after repair. A 1 MHz transducer was used for all inspections. The following is a summary of the NDI results and failure modes for the CACRC wet lay-up repairs with the highest and lowest residual strengths. C-scans and post-test pictures of the repairs with the lowest residual strengths are shown in figures 68–70, with scans of panels 68 and 69 not showing any indication of an improper bond. C-scans and post-test pictures of three of the repairs with the highest residual strengths are shown in figures 70–73.

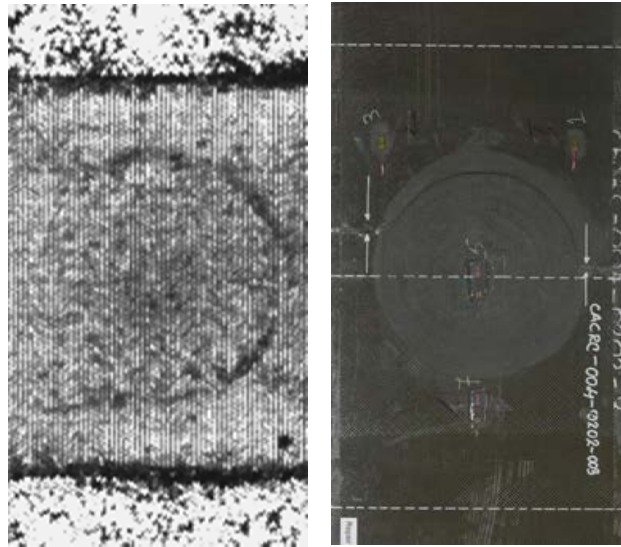


Figure 68. CACRC-004-0202-003-W-RC-ETW (element 21), TTU scan, pre- and post-test picture (adhesion failure)

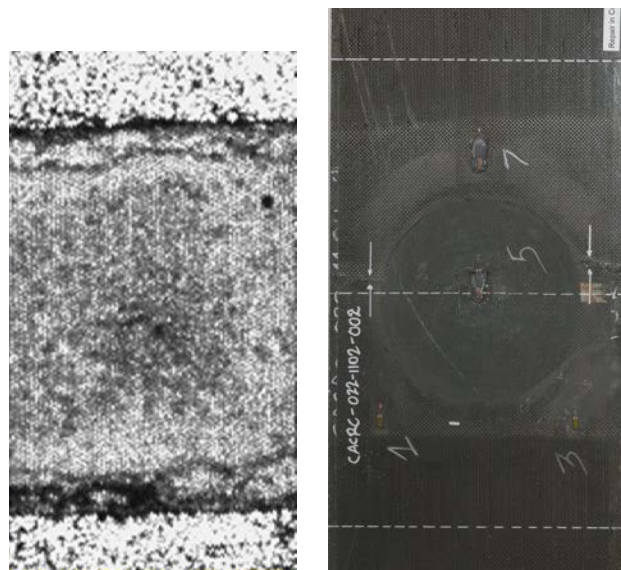


Figure 69. CACRC-022-1102-002-W-RC-ETW (element 23), TTU scan, pre- and post-test picture (adhesion failure)

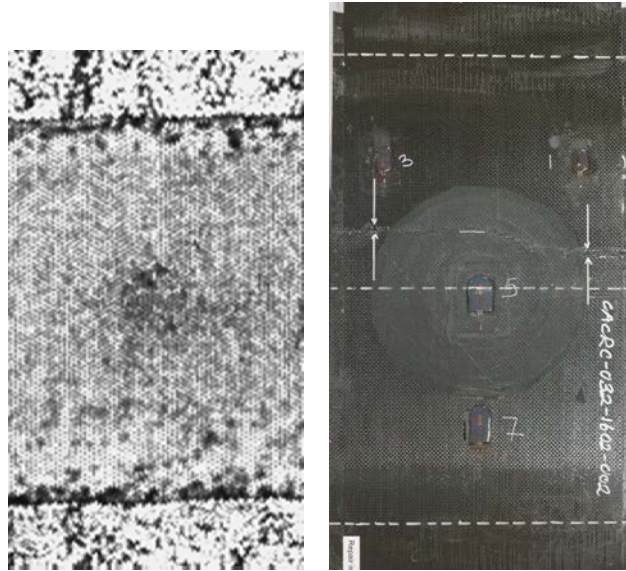


Figure 70. CACRC-032-1602-002-W-RC-ETW (element 32), TTU scan, pre- and post-test picture (understrength repair, facesheet compression failure through repair)

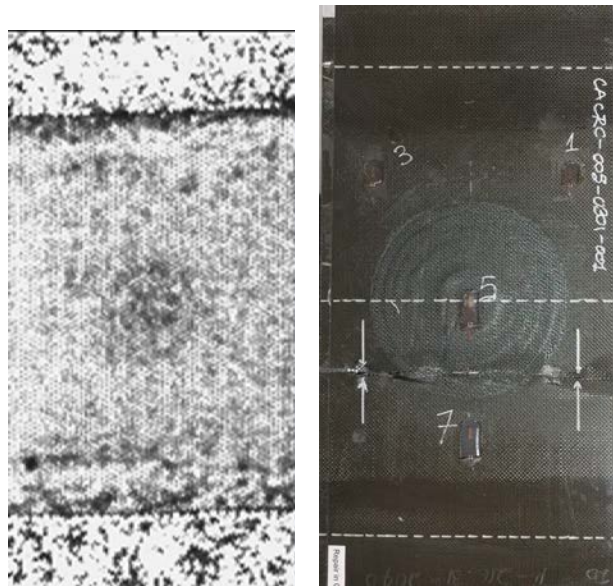


Figure 71. CACRC-005-0301-001-W-RC-ETW (element 10), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)

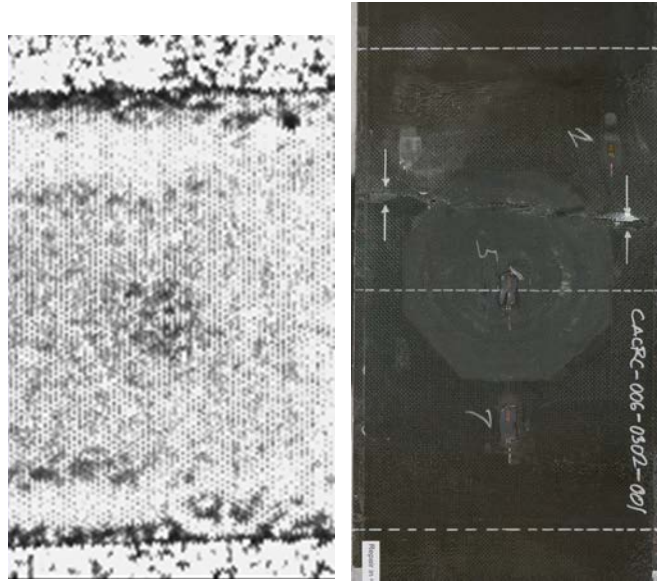


Figure 72. CACRC-006-0302-001-W-RC-ETW (element 24), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)

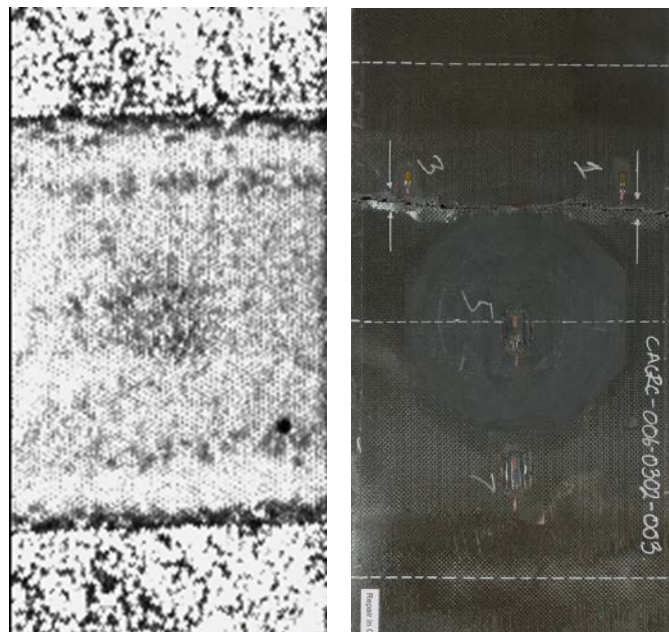


Figure 73. CACRC-006-0302-003-W-RC-ETW (element 27), TTU scan, pre- and post-test picture (facesheet compression failure through the repair)

4.4.10 Wet Lay-Up Repair Post-Test Analysis

Post-test physical, thermal, and optical analyses of all CACRC wet lay-up repairs and a thorough review of the process records for these repairs were completed. The analysis was conducted on the understrength repairs but also on repairs that demonstrated good performance and residual strength. The goal was to find the physical and thermal properties of the parent and repair materials

and to identify possible anomalies that might have contributed to the low-residual-strength repairs. A post-test analysis map is shown in figure 56. DMA, DSC, and physical test samples were extracted from the center of the repair and from parent material adjacent to the repair, as shown in the figure. Section cuts along the width of the repair element were used to inspect the quality of the parent and repair laminate, as shown in the figure.

Reviewing the failure modes of all CACRC wet lay-up repairs, it was found that three elements yielded adhesion failures. Repair records for these elements revealed that an incorrect cure cycle was used for one of the repairs, resulting in the over cure of the repair. A two-step cure was used for the second repair, and a minimum dwell time was used for the third repair.

A cross section of CACRC-023-1201-002 (sections B and C), through the center section of the CACRC wet lay-up repair, is shown in figures 74 and 75. Both figures show porosity in the repair, consistent with the physical test results. Similarly, a cross section of CACRC-006-0302-003 (sections B and C), through the center section, is shown in figures 76 and 77. Both figures show lower porosity levels in the repair, consistent with the physical test results.

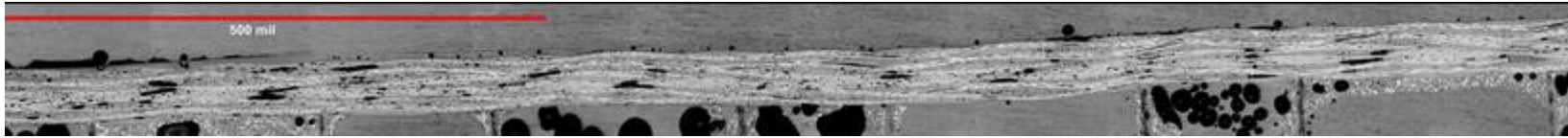


Figure 74. CACRC-023-1201-002 section B



Figure 75. CACRC-023-1201-002 section C



Figure 76. CACRC-006-0302-003 section B



Figure 77. CACRC-006-0302-003 section C

5. CONCLUSIONS AND RECOMMENDATIONS

The long-term durability of adhesively bonded structures and repairs is a key element in the acceptance and implementation of bonded technology by original equipment manufacturers and operators in the repair of composite primary structural elements. Weak interfacial bonds between composite substrates, resulting from a deficient process, are not detectable by current inspection methods and will likely degrade as the component is in service, subjected to loading and the environment. With the lack of inspection methods to ensure the integrity of a composite substrate's interface prior to bonding or to detect deficient bonds, there is a concern that undetected weak bonds or understrength repairs may further deteriorate in service, potentially leading to the failure of the repaired part. A robust infrastructure for maintenance and repair is necessary to ensure the airworthiness and long-term durability of composite airframe components.

The objective of this research work was to evaluate the existing Commercial Aircraft Composite Repair Committee (CACRC) standards and approved materials for repair of composite structures, to assess the repair process variability between depots using the same repair document procedures (similar to industry standard repair manuals) and CACRC repair techniques and materials provided to all the depots, and to investigate the variability associated with technician training (minimal level of experience versus extensive experience) on the performance of the repair. The ultimate goal was to compare the strength of the different repairs to a set of control "pristine" panels and to a set of open-hole scarfed panels simulating a patch-off condition and to evaluate the environmental effects on the static and residual strength after fatigue of these repairs. The objectives of this research work were met by round robin testing of these repairs at different depots. This research work was reviewed by CACRC and industry members and feedback received was incorporated into this report [36–40]

Results of the study showed that the CACRC standards cannot be used as a sole document to repair a composite part. These standards represent best practices/techniques for repair, as intended; therefore, a part-specific document is required. The CACRC standards can, however, be used along with a structural repair manual or other part-specific repair document. It is ultimately the repair designer's responsibility to select which standards to use for the specific repair.

The study also showed variability in the repair residual strength results between depots and mechanics and the wet lay-up repairs yielded a higher scatter than the prepreg repairs. Results underscored that repairmen experience alone is not a predictor of repair performance. The feedback received from depot personnel and the results of the round robin testing demonstrate the importance of workforce education and training for the proper execution of bonded repairs to composite substrates. Detailed repair records must be kept to ensure repair process control, stability and to detect and correct for process failures and deviations. Part and process specific training of the composite repair workforce, taking into account the process learning curve, is strongly recommended. Process inspection and quality assurance oversight is also strongly advocated.

Results of the study also demonstrate the importance of repair process development, substantiation and execution. Process substantiation should include understanding of the critical process steps and parameters affecting the repair performance and the consequences of bad process implementation. Because of the chemical characteristics of the various systems used for bonding

and repair, it is very important to understand the capabilities and limitations of the specific systems especially when they are close to the end of their storage and/or work lives. It is also important to understand the importance of proper bagging and the effects of cure cycle parameters such as temperature ramp-up rates, dwell time and vacuum levels on the performance of the repair. The use of adequate processes specific to the materials used is key to the structural integrity of the repaired part. Caution should be exercised when applying results from one material system to the next.

Results from this research yielded the following critical composite repair processing parameters that could affect the strength of the repair:

Environment/ Timeframe for Repair Execution

- Repair Station Environment
- Timeframe for repair performance and execution

Repair materials

- Repair Material out time and storage life
- Batches of materials used

Panel Preparation/Inspection Prior to Repair

- Surface preparation
- Quality of the repair scarf (morphology)
- Fitness of the interface for bonding (pre-bond moisture, contamination)

Repair Application

- Number of filler plies (when applicable)
- Ply alignment/ sequence
- Resin Mixing Ratios (Wet Lay-up Repairs)
- Resin Work Life (Pot Life, Wet Lay-up Repairs)

Repair Cure

- Repair Bagging Scheme and Materials
- Heat Blanket and Thermocouple Installation (Hot Bonder Calibration)
- Time lag between drying and final cure
- Repair Cure Cycle Ramp Up Rate
- Repair Cure Dwell Time
- Vacuum Level Achieved during Repair cure (sea level, high altitude)

As shown by the results, a deficient process may result in understrength or completely failed repairs whereas a robust repair design and execution will yield strong durable bonded repairs.

Knowledge transfer in the form of training, validated repair instructions and repair records and documentation are integral to ensuring repair process repeatability, stability and thus structural integrity of the repaired component. Process documentation and QA oversight is necessary to ensure strict adherence to the process.

6. REFERENCES

1. NASA Report. (2009). NASA Composite Materials Development: Lessons Learned and Future Challenges. (LF99-9370).
2. Chesmar, E. (2004). *Repair and Maintenance Implementation: Airline Experience, Problems, Concerns and Issues*. Paper presented at the FAA Bonded Workshop.
3. CMH-17-3G (2016). *Composite Materials Handbook Volume 3 (working draft), Polymer Matrix Composites Materials Usage, Design and Analysis*. Wichita, KS: Wichita State University.
4. SAE (1997). Design of Durable, Repairable and Maintainable Aircraft Components – SAE Commercial Aircraft Composite Repair Committee. (SAE AIR 6902, AE 27).
5. FAA. (2009, September). Advisory Circular 20-107 B, *Composite Aircraft Structure*. Washington, D.C.: Government Publishing Office.
6. Baker, A. A. (1994). *Bonded Composite Repair of Metallic Components — Overview of Australian Activities*. Paper presented at the 79th Meeting of the AGARD Structures and Materials Panel on Composite Repair of Military Aircraft Structures, Seville, Spain.
7. Davis, M. J., Chester, R. J., Perl, D. R., Pomerleau E., Vallerand, M. (1998). *Honeycomb Bond and Core Durability Issues*. Paper presented at Experiences with CREDP Nations, Aging Aircraft Conference, Williamsburg, VA.
8. Davis, M., Bond, D., (1999). Principles and Practices of Adhesive Bonded Structural Joints and Repairs. *Journal of Adhesion and Adhesives*, 19(2–3), 91–105.
9. FAA Report. (2004). Bonded Repairs of Aircraft Composite Sandwich Structures. (DOT/FAA/AR-03/74).
10. FAA Report. (Under Final Review, publication date TBD). Effects of Process Parameters on Bonded Repairs of Composite Airframe Structures. (DOT/FAA/xx/xx).
11. Abdelkader, A. F., White, J. R. (2005). Water Absorption in Epoxy Resins, The effects of the Cross Linking Agent and Curing Temperature. *Journal of Applied Polymer Science*, 98(6), 2544–2549.

12. Davis, M. (2004). *Best practices in adhesive bonding*. From Bonded Structures Workshop, Seattle, WA. Retrieved from <http://www.niar.wichita.edu/niarworkshops/Workshops/BondedStructuresWorkshop,June2004,Seattle/tabid/104/Default.aspx>
13. SAE. (2011). Carbon Fiber Fabric Repair Prepreg, 125°C (250°F) Vacuum Curing -Part 1-General Requirements (SAE AMS 3970/1A).
14. SAE. (2011). Carbon Fiber Fabric Repair Prepreg, 120°C (250°F) Vacuum Curing -Part 2-Qualification Program for Fiber, Fabric, Carbon Prepreg, Film adhesive and Non-Structural Glass prepreg. (SAE AMS 3970/2A).
15. SAE. (2011). Carbon Fiber Fabric Repair Prepreg, 120°C (250°F) Vacuum Curing -Part 3-Purchasing Specification for Carbon Prepreg. (SAE AMS 3970/3A).
16. SAE. (2011). Carbon Fiber Fabric Repair Prepreg, 120°C (250°F) Vacuum Curing -Part 4-Purchasing Specification for Film Adhesive. (SAE AMS 3970/4A).
17. SAE. (2011). Carbon Fiber Fabric Repair Prepreg, 120°C (250°F) Vacuum Curing -Part 6-Carbon Fiber Fabric Reinforced Epoxy Prepreg for Repair, Plain Weave, 193g/m², Adhesive Film for Repair, Non-Structural Glass Fiber Fabric Reinforced Epoxy Prepreg, 105g/m². (SAE AMS 3970/6).
18. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 0 – Introduction (SAE AMS 2980A).
19. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 1 – General Requirements. (SAE AMS 2980/1A).
20. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 2 – Qualification Program. (SAE AMS 2980/2A).
21. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Purchasing Specification – Fabric. (SAE AMS 2980/3A).
22. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Purchasing Specification – Resin. (SAE AMS 2980/4A).
23. SAE. (2006). Carbon Fiber Fabric and Epoxy Resin Wet Lay-Up Repair Material Part 5 – Material Specification: Carbon Fiber Fabrics, Plain Weave, 193g/m² and Epoxy Resin. (SAE AMS 2980/5).
24. SAE. (2011). Masking and Cleaning of Epoxy and Polyester Matrix Thermosetting Composite Materials. (SAE ARP 4916).

25. SAE. (2015). Machining of Composite Materials, Components and Structures (SAE AIR 5367).
26. SAE. (1987). Cloths, Cleaning for Aircraft Primary and Secondary Structural Surfaces. (SAE AMS 3918C).
27. SAE. (2011). Drying of Thermosetting Composites. (SAE ARP 4977).
28. SAE. (2011). Heat Application for Thermosetting Resin Curing. (SAE ARP 5144).
29. SAE. (2011). Vacuum Bagging of Thermosetting Composite Repairs. (SAE ARP 5143).
30. SAE. (2011). Composite Repair NDI/ NDT Handbook. (SAE ARP 5089).
31. SAE. (2014). Mixing Resins, Adhesives and Potting Compounds. (SAE ARP 5256).
32. SAE. (2011). Impregnation of Dry Fabric and Ply Lay-Up. (SAE ARP 5319).
33. ASTM Standard D5229 / D5229M-14, "Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials," ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/D5229_D5229M-14, www.astm.org.
34. ASTM Standard E4-03, "Standard Practices for Force Verification of Testing Machines," ASTM International, West Conshohocken, PA, 2003, DOI: 10.1520/E0004-03, www.astm.org.
35. ASTM Standard D7249-06, "Standard Test Method for Facing Properties of Sandwich Constructions by Long Beam Flexure," ASTM International, West Conshohocken, PA, 2006, DOI: 10.1520/D7249_D7249M-06, www.astm.org.
36. Tomblin, J., Lamia, S. (2011). *CACRC Depot Bonded Repair Round Robin Investigation*. Paper presented at the FAA Joint Advanced Materials and Structures Center of Excellence 7th annual review meeting.
37. Tomblin, J., Lamia, S. (2012). *CACRC Depot Bonded Repair Round Robin Investigation*. Paper presented at the FAA Joint Advanced Materials and Structures Center of Excellence 8th annual review meeting.
38. Tomblin, J., Lamia, S. (2013). *CACRC Depot Bonded Repair Round Robin Investigation*. Paper presented at the FAA Joint Advanced Materials and Structures Center of Excellence 9th annual review meeting.
39. Tomblin, J., Lamia, S. (2014). *CACRC Depot Bonded Repair Round Robin Investigation*. Paper presented at the FAA Joint Advanced Materials and Structures Center of Excellence 10th annual review meeting.

40. Tomblin, J., Lamia, S. (2015). *CACRC Depot Bonded Repair Round Robin Investigation*. Paper presented at the FAA Joint Advanced Materials and Structures Center of Excellence 11th annual review meeting.